

BRILLOUIN AMPLIFICATION- A POWERFUL NEW SCHEME FOR MICROWAVE PHOTONIC COMMUNICATIONS

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ABSTRACT

We introduce the Brillouin selective sideband amplification technique and demonstrate many important applications of this technique in photonic microwave systems, including efficient phase modulation to amplitude modulation conversion, photonic frequency multiplication, photonic signal mixing with gain, and frequency multiplied signal up conversion. Using the Brillouin amplification, we also demonstrated an all optical opto-electronic oscillator that eliminate the use of the power consuming and bulky electrical amplifiers.

INTRODUCTION

Brillouin amplification in digital photonic systems has been extensively studied by many authors. Unfortunately, it has been proved to be impractical due to its narrow bandwidth and high spontaneous emission noise.^{1,2} Perhaps because of such unsuccessful attempts in the digital domain, the application of Brillouin amplification in analog photonic systems was seldom investigated. In fact, the related Brillouin scattering is generally considered to be harmful and extensive efforts have been devoted to minimize its effect.

We show in this paper both experimentally and analytically that Brillouin amplification can drastically improve the performance and extend the functionality of an analog photonic system if properly used. We introduce a powerful selective sideband amplification concept and demonstrated many important applications in microwave photonic communication systems that fully exploit the advantages of Brillouin amplification and circumvent its disadvantages.

BRILLOUIN AMPLIFICATION OF ANALOG SIGNALS

Brillouin scattering measurement

Stimulated Brillouin Scattering (SBS) is the most sensitive nonlinear optic effect in optical fibers with a threshold power as low as few milliwatts. If the input optical power in a photonic link exceeds the SBS threshold, the forward going optical signal will be scattered back due to its interaction with an acoustic grating it generated via electrostrictive effect. Consequently, the forward going signal at the output will be saturated with the increase of the input power.

Because the acoustic grating is moving in the direction of the pump light, the frequency of the backscattered light will be downshifted by ν_B via Doppler effect:

$$\nu_B = 2n v_a / \lambda_p, \quad (1)$$

where v_a is the velocity of the acoustic wave in the fiber-, n is the refractive index of the fiber, and λ_p is the wavelength of the pump wave.

Fig. 1 a is the experimental set up for measuring the SBS threshold and power. In the experiment, a fiber length of 12.8km was used and care was taken to minimize backreflections from various device's. The backscattered power is measured at port 2 of the coupler and the input power to the fiber was monitored at port 4 of the same coupler. Fig. 1b show the SBS power and throughput power after the 12.8km fiber. The vertical axis of the Fig. 1b is in log scale to show data of small value and the insert shows the same data in linear scale. It is evident from the insert that the SBS threshold is about 10 mW. Above the threshold power, the throughput is saturated and the SBS power increases rapidly with the input power.

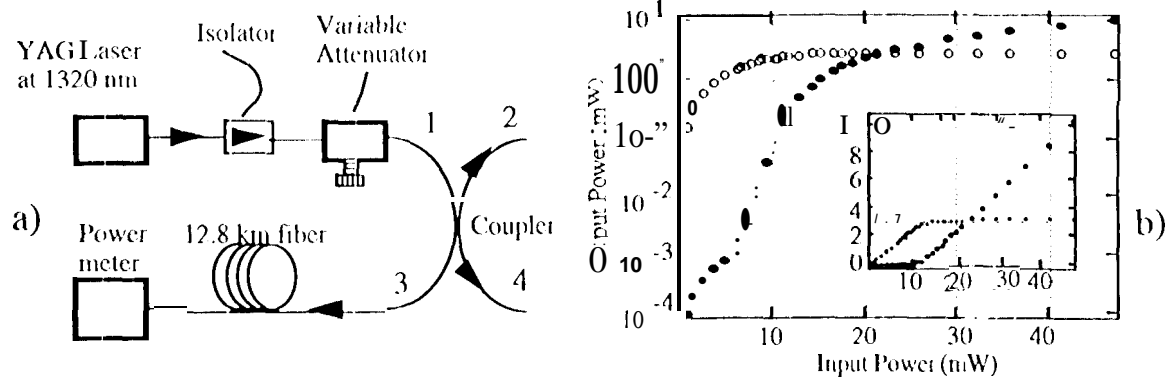


Fig. 1. a) Stimulated Brillouin Scattering Measurement Setup. b) Throughput power and SBS power as a function of input power plotted on a log scale. The insert is the same data plotted on linear scale. O: throughput power. ●: SBS power.

By introducing a reflection at port 4 in Fig. 1a, we measured the beat frequency spectrum of the Brillouin scattering signal with the original pump signal using an RF spectrum analyzer. The peak of the spectrum is at 12.8 GHz and the 6 dB bandwidth is about 13 MHz. This result indicates that the frequency of the Brillouin scattering is shifted from the pump signal by 12.8 GHz and the 3-dB optical bandwidth of the Brillouin scattering is about 13 MHz. The line width and the frequency of the Brillouin scattering is found to be independent of the pump power.

Brillouin Amplification

It is important to notice from Fig. 1b that even below the threshold, there is a substantial spontaneous Brillouin scattering presence. If a narrow-band seed signal with a frequency of $\nu_p - \nu_B$, where ν_p is the frequency of the pump laser, is injected into the fiber from the opposite end of the pump, the interaction of the seed signal with the pump will greatly enhance the induced acoustic grating, causing more backscattering of the pump into the seed and effectively amplifying the seed signal. In other words, the influence of the seed signal converts the spontaneous Brillouin scattering into a stimulated Brillouin scattering, at a pump power much below the SBS threshold. The stimulated backscattering light will add up in phase with the seed and greatly amplify the seed. This process is called Brillouin amplification.¹ Because of its narrow bandwidth, Brillouin amplification was generally considered to be impractical for amplifying digital signals of much larger bandwidth. As will be discussed below, one may get around this limitation in many applications by using the concept of selective sideband amplification unique to Brillouin amplification.

The Concept of Selective Sideband Amplification

An optical signal may typically include an optical carrier and lower and upper modulation sidebands, with the sidebands much weaker than the carrier, as shown in Fig. 2a. The received signal in the photodetector is the beat between the carrier and the sidebands. If an optical amplifier, such as a semiconductor optical amplifier (SOA), an Er^{3+} -doped fiber amplifier (EDFA), or a fiber Raman amplifier, is used to amplify the signal, both the strong carrier and the weak sidebands are amplified. This process is not efficient because the already strong carrier may saturate the amplifier, causing insufficient amplification of the weak sidebands. In addition, the strong amplified carrier may also saturate the photodetector, further limiting the amplification of the information-carrying sidebands.

Fig. 2a and Fig. 2b show the concept of Brillouin selective sideband amplification. The narrow bandwidth of Brillouin amplification is used to its advantage to selectively amplify one of the weak sidebands and leave the strong carrier unchanged. The received RF signal in the photodetector will be the beat between the strong carrier and the amplified sideband. This way, we can dramatically increase the modulation index of the received RF signal and amplify it. In the experiment, one can either tune the frequency of the pump laser or the frequency of the signal laser so that one of the modulation sideband coincides with the frequency of the Brillouin scattering and this sideband will be amplified. Such an amplification scheme is much more efficient than other optical amplification schemes because all Brillouin scattering energy from the pump laser goes into

the needed weak sideband. Furthermore, because the strong carrier is not amplified, the saturation of the receiving photodetector can be avoided.

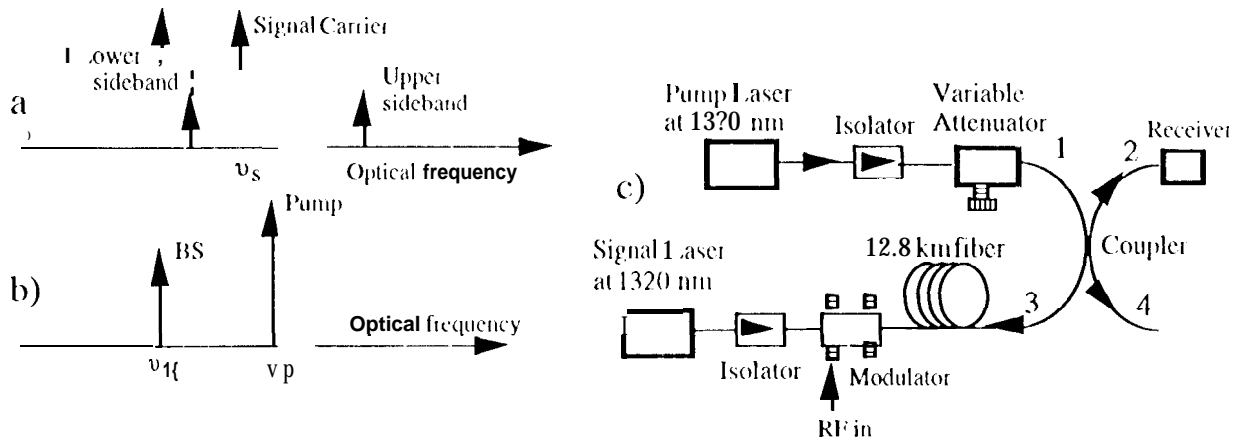


Fig.2 a) The typical spectrum of an RF signal imposed on an optical carrier. b) The spectrum diagram showing the frequencies of the pump and the Brillouin scattering. When the frequency of one of the sidebands is coincident with the frequency of the Brillouin scattering, it will be amplified. c) The experimental setup for demonstrating Brillouin Selective Sideband Amplification.

Taking an optical signal having a carrier of 5 mW and sidebands of 0.1 mW as an example, one can clearly see the efficiency of the selective sideband amplification. The received electrical power after the photodetector is proportional to 5×0.1 . To amplify this beat signal by 6 dB, an optical power of at least 5.1 mW is needed if both the carrier and the sidebands are amplified (doubling the power of both the carrier and the sidebands). However, if only a needed sideband is amplified, only 0.4 mW of optical power is needed (increasing the sideband 4 times).

Fig. 2c is the experimental setup for demonstrating selective sideband signal amplification using Brillouin scattering. In the experiment, a signal laser (diode pumped YAG laser) at 1320 nm was used to carry an RF signal. The RF signal is imposed onto the carrier by using a LiNbO₃ Mach-Zehnder modulator. The signal light is finally injected into the 12.8 km fiber from the opposite end of the pump laser (also a diode pumped YAG laser). Isolators were used in front of the pump and signal lasers to prevent light from entering each other.

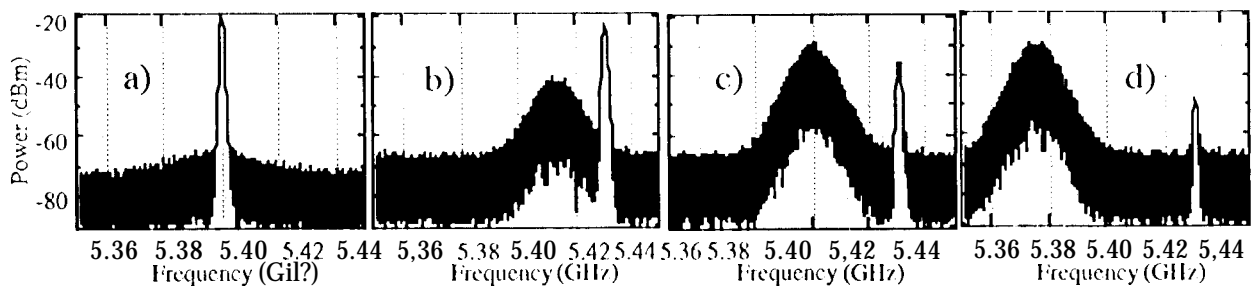


Fig. 3 Experimental results demonstrating Brillouin Selective Sideband Amplification technique. a) Pump is tuned to be aligned with a signal sideband. An RF gain of 31.5 dB is observed. b) The pump laser is tuned slightly misaligned with the signal sideband and the gain decreased to 28.7 dB. c) The pump laser is further tuned away and the gain decreased to 16.5 dB. d) The pump laser is tuned two gain bandwidth away and the RF gain decreased to 3 dB. The frequency span of the measurement is 100 MHz and the noise bandwidth is 1 MHz. The input RF signal is at 5.43 GHz with a power of -2.17 dBm.

Fig. 3a to 3d are the experimental results demonstrating the amplification of the RF signal by Brillouin scattering. In the figure, the broad peak is the beat between the signal carrier and the Brillouin scattering. The narrow and clean peak is the received RF signal or the beat of the signal carrier and the RF modulation sidebands. It is evident that when the lower sideband of the RF signal is aligned with the Brillouin scattering

peak, it is amplified with a gain of more than 30 dB. When the Brillouin scattering peak is tuned away from the sideband, the amplification diminishes gradually.

Properties of Brillouin Amplification

Fig. 4a to 4d show the amplified signal level and noise floor corresponding to increasing input RF power. From the figures one can see that because of the gain saturation, weaker input signals experience more gain than the stronger ones. However, at the same time the amplifier noise floor corresponding to the weaker input signal is also larger.

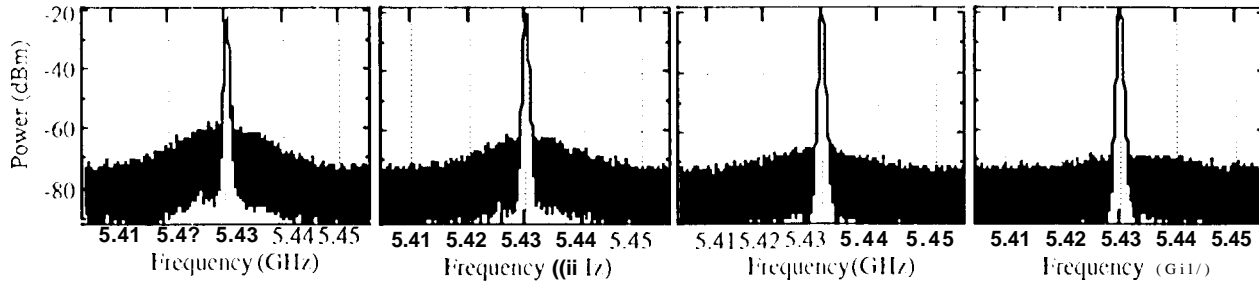


Fig 4 Experimental results showing that as the input RF power increases from left to right, the output signal level stays the same, resulting in a decreased gain but an increased signal to noise ratio (note the noise floor decreases at the same time). From (a) to (d), the input RF power are -12.17, -7.17, -2.17, and 2.83 dBm respectively and the corresponding gain are 38.5, 35, 31.5, and 27.17 dB. In all the measurement, the span is 50 MHz and the resolution bandwidth is 300 kHz.

The RF link gain (defined as the difference of RF output power from the photodetector and the RF input power to the modulator in dB) as a function of RF input power is shown in Fig. 5a. With a pump power of only 12.23 mW, a small signal RF link gain of more than 20 dB at 5.5 GHz is achieved. As a comparison, the RF link loss without Brillouin scattering amplification is about -41 dB. This accounts for a total RF signal amplification of 61 dB.

Finally, Fig. 5b shows the RF signal gain from the Brillouin scattering as a function of optical pump power for different input RF power. It is evident that a substantial gain of the signals can be achieved even when the optical power is much less than the SBS threshold. At high pump powers, the gain also saturates.

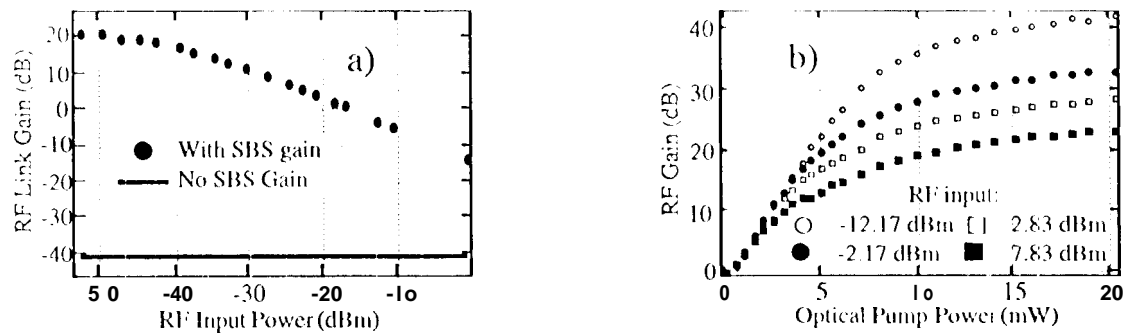


Fig. 5. a) RF link gain as a function of RF input power to the modulator. A small signal link gain of 20 dB was obtained with only 2.61 mW optical power in the photodetector. The gain decreases at high input RF power levels. The optical pump power in the experiment is 12.23 mW. b) The gain of RF signals vs. optical pump power for different RF input powers to the modulator. Substantial RF gain was obtained even when the pump power is much lower than the SBS threshold level of 10 mW. Note that the gain saturates at high optical pump power.

From the experimental results above one can see that the Brillouin amplification has the following properties. First, it is very efficient and requires very low pump power. A DFB laser with a few milliwatts output power is sufficient to achieve adequate signal amplification. Consequently it is much less expensive to implement than an EDFA or an SOA. Second, it has very narrow gain bandwidth which is advantageous for the efficient selective sideband amplification, however is disadvantageous for amplifying signals with wide bandwidths. Third, the weaker signal generally gets a higher gain, however accompanied by a higher amplifier noise. The noise is due to the spontaneous Brillouin scattering of the pump laser. If the seed signal is

sufficiently strong, the stimulate Brillouin **scattering** induced by the seed will dominant and deplete the energy that may otherwise goes to the noise (spontaneous Brillouin scattering). For an externally modulated link, we found experimentally that the amplifier noise is insignificant if the input RF signal is sufficiently strong that the RF gain is less than 30 dB. Finally, the gain saturates for large signals with fast response time. As in an SOA, this fast gain saturation will generate intermodulation products and distort the signal. In the following section, we will discuss and demonstrate many applications in which the advantages of the Brillouin amplification can be fully utilized, while its limitations can be circumvented.

APPLICATIONS OF BRILLOUIN AMPLIFICATION

1. Phase Modulation To Amplitude Modulation Conversion

In all communication systems, no matter how the signal is being sent (either amplitude modulated, frequency modulated, or phase modulated), the received signal must finally be converted to amplitude modulation. Therefore, efficient and stable conversion of phase modulation to amplitude modulation is extremely important for a system employing phase modulation scheme.

Almost all the phase to amplitude conversion is accomplished by either the homodyne method in which a phase modulated optical carrier is made to beat with an unmodulated optical carrier of the same frequency, or the heterodyne method in which the phase modulated optical signal is made to beat with another optical carrier of different frequency. A good example of the homodyne method is the Mach-Zehnder modulator in which an optical carrier is first splitted into two, one of them is then phase modulated. The modulated half and the unmodulated half finally combines in the photodetector to produce a corresponding amplitude modulation.

One major problem associated with the homodyne and heterodyne is the stability, especially when the two beating optical signals are from different sources. Although optical homodyne and heterodyne communication systems were proposed and extensively studied by many researchers, they never become practical due to the **stability** problems. Even the commonly used Mach-Zehnder modulator still have drift problems caused by differential path length fluctuations of the two optical arms.

Another problem is the optical insertion loss, taking again a Mach-Zehnder modulator as an example. As mentioned before, in the Mach-Zehnder modulator the input optical carrier must be splitted into two arms and recombined at the output. Practically, both the beamsplitter and the beam combiner will introduce optical loss. In addition, in order for the modulator to function properly, the modulator must be biased at 50% transmission peak which introduces another 3 dB optical loss.

It is well known that the phase modulation of an optical carrier introduces many sidebands, each has certain phase and amplitude relationship with the carrier and with each other. Why don't the sidebands beat with the carrier and beat with each other to produce amplitude modulations? They do beat, however because of the phase and amplitude relationship of the side bands, to each beat signal, there always is a corresponding beat signal which has the same amplitude and frequency but opposite phase. They cancel each other out perfectly and produce no net amplitude modulation. Amplitude modulation will result if this perfect balance is broken.

We demonstrate that Brillouin amplification is ideal for the phase modulation to amplitude modulation conversion. Because of the extreme narrow bandwidth of the Brillouin gain, selective amplification of a particular sideband is possible. The amplification of a single or multiple modulation sidebands will break the perfect amplitude balance of sidebands of a phase modulation and cause the phase modulation to convert to an amplitude modulation. The converted amplitude modulation is extremely stable, immune to the fluctuations in the frequency of the optical carrier, the temperature, and the fiber length. In addition, the conversion is much more efficient than any other method due to the gain obtained by the sidebands.

The experimental setup is similar to Fig. 2c except that a phase modulator is used to replace the Mach-Zehnder modulator. The spectrum of the phase modulated signal laser is shown in Fig. 6a and the spectrum of the pump laser and its Brillouin scattering is shown in Fig. 6b. In order to amplify a phase modulation sideband, either the pump laser frequency or the signal laser frequency should be tuned so that the sideband is aligned with the Brillouin scattering frequency (about 12.8 GHz below the pump laser frequency). The beat between the

amplified sideband and the carrier is the dominant contributor of the converted amplitude modulation. In the demonstration, an RF signal was used to drive the phase modulator and the output from the photodetector is connected to an RF spectrum analyzer. Without the Brillouin pump, no RF signal was observed. When the pump is turned on and its frequency is aligned with the -1 order sidebands, a strong signal shown in Fig. 6c was detected by the spectrum analyzer, indicating an efficient phase modulation to amplitude modulation conversion.

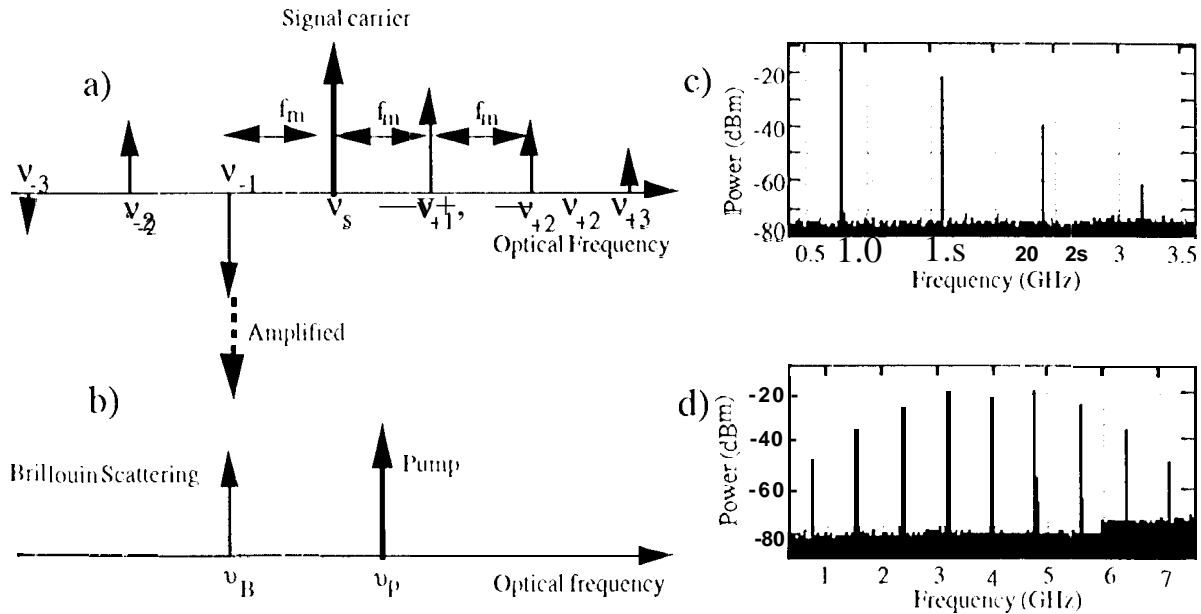


Fig. 6 Concept and demonstration of Brillouin phase modulation to amplitude modulation conversion a) phase modulation spectrum. b) The spectrum of the pump laser and its Brillouin scattering. When one of the phase modulation sideband is aligned with the Brillouin frequency, it will be amplified and break the perfect amplitude balance of the phase modulation. c) The received RF spectrum of a phase modulated signal of 800 MHz when the -1 sideband is amplified by Brillouin amplification. The RF input to the modulator is 10.83 dBm and the resolution bandwidth of the measurement is 100 kHz. d) The received RF spectrum of the same phase modulated signal when -5 sideband is amplified. The input RF power is 20 dBm and the resolution bandwidth is 30 kHz.

2. Frequency Multiplication

Phase modulation of an optical carrier generally generates many sidebands. As shown in Fig. 6, one may selectively amplify a higher order sideband and obtain beat frequencies multiple times of the frequency of the RF driving signal. Fig. 6c and Fig. 6d show the received RF spectrum when the -1 order sideband and -5 order sideband were amplified respectively. It is evident from Fig. 6d that frequency components as large as 9 times of the frequency of the driving signal is efficiently generated. Note that the phase modulator used has a specified bandwidth of only 0.5 GHz. However, with the aid of the selective Brillouin amplification, it generated frequency as high as 7 GHz. With the same token, it is reasonable to expect that a common 10 GHz modulator can be used to obtain signals exceeding 100 GHz, especially when it is combined with the harmonic carrier generation technique of S. Papert et al.³ This efficient Brillouin frequency multiplication is therefore very useful for generating millimeter wave photonics signals, without the needs of using expensive high speed modulators, using high frequency sources, and overly driving the modulator.

3. Photonic signal mixing with Brillouin gain

The concept of photonic RF signal up conversion and down conversion is very attractive because it has virtually infinite isolation between the local oscillator (LO), radio frequency (RF), and intermediate frequency (IF) ports. In addition, one step conversion from RF to IF or from IF to RF can be achieved no matter how large the IF and RF frequency different from each other. Photonic mixing has been demonstrated⁴ by many authors using two cascaded Mach-Zehnder electro-optic amplitude modulators. One of the modulators is driven by a LO signal and the other modulator is driven by a signal. The beating between the carrier and the signal sidebands in the photodetector converts the signal back to electrical domain, while the beating between the LO

modulation side bands and the signal modulation sidebands in the photodetector produces the down and Up converted signal. Because the I.O sidebands are always much weaker than the carrier, the conversion process is always accompanied with a large loss

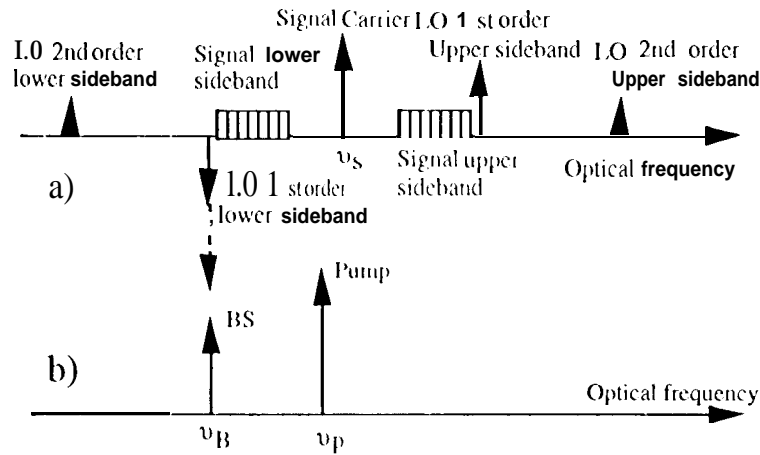


Fig. 7 Illustration of photonic signal mixing with Brillouin gain.

As illustrated in Fig. 7a and Fig. 7b, using Brillouin amplification one can dramatically increase one of the I.O modulation sidebands when it aligned with the Brillouin frequency. In the illustration, the lower I.O modulation sideband is amplified. Since the downconverted signal is the beat between the lower I.O sideband and the lower RF sideband plus the beat between the upper I.O and upper RF sideband, amplifying one of the I.O sideband will increase the downconverted signal. Similarly, since the up-converted signal is the beat between the upper I.O sideband and the lower RF sideband plus the beat between the lower I.O sideband and the upper RF, the amplification of one of the I.O will cause the upconverted signal to be amplified. If the I.O sideband is amplified to be larger than the carrier, the conversion will then experience a gain.

It is important to notice that the Brillouin amplification assisted signal mixing described above is independent of the bandwidth of the RF signal in spite of the narrow bandwidth of the Brillouin amplification. This is because only the single tone I.O sideband band is being amplified. Therefore, using Brillouin amplification for signal mixing can avoid the shortfall of its narrow amplification bandwidth. Although it is possible to amplify the RF instead of I.O to achieve the same RF amplification, the signal bandwidth will be limited by the Brillouin amplification bandwidth.

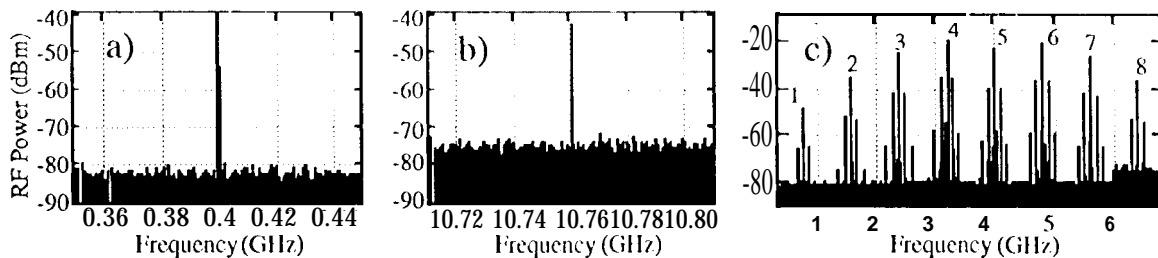


Fig. 8 Experimental result demonstrating amplified photonic mixing and frequency multiplied signal up conversion. a) Spectrum of down converted signal. b) Spectrum of up converted signal. c) The spectrum of a frequency multiplied and up converted signal. For a) and b), the I.O and RF frequencies are 5.18 and 5.5873 GHz respectively. For c), the RF frequency is 0.1 GHz and the I.O frequency is 0.8 GHz. As indicated in c), the 1st signal up converted to as high as 6.4 GHz with an I.O of only 0.8 GHz. The numbers on top of each peak indicate the number of harmonics of the I.O.

We performed two experiments to demonstrate the photonic mixing with Brillouin gain. The setup for the first experiment is similar to Fig. 2c. In the experiment, the modulator used has two independent RF input ports with an isolation over 40 dB. An I.O signal of 4.83 dBm at 5.18 GHz was injected into one of the port and an RF signal of -5 dBm at 5.5873 GHz was injected into the other port. The modulator was biased at 50% of the

transmission peak. Without the Brillouin amplification, the total optical power at the detector is 0.314 mW, the received I.O is -40 dBm, and the received RF is -52 dBm. At a pump power of 12.112 mW, the Brillouin amplification increased the total optical power at the detector to 2.61 mW and increased the I.O power to -15 dBm. The received down converted signal is -40 dBm and the up converted signal is -42 dBm, resulted in a down conversion gain of 12 dB and up conversion gain of 10 dB. The spectra of the amplified I.O, down converted signal and Up converted signal are shown in Fig. 8a and Fig. 8b. Similar results also obtained by cascading two Mach-Zehnder modulators.

With the concept of Brillouin phase modulation to amplitude modulation conversion discussed above, we also demonstrated using two cascaded phase modulators to replace the Mach-Zehnder amplitude modulators for achieving efficient photonic mixing, as shown in Fig. 9a. The elimination of the two Mach-Zehnder amplitude modulators will automatically eliminate a total of 6 dB optical loss associated with biasing the modulators, resulting in an RF gain of 12 dB. In addition, it will also eliminate the bias drift, thus making the photonic link more stable.

5. Frequency Multiplied Signal Up Conversion

In the experiments described above, if a higher order I.O modulation sideband in Fig. 7a is amplified, the beat between the higher order I.O sideband with the signal sidebands not only will convert the RF signal to the I.O frequency, but also to the multiple of the I.O frequency. We demonstrated this frequency multiplied signal up conversion with two 0.5 GHz phase modulators in Fig. 9a and the results is shown in Fig. 8c. With the amplification of the -5 order sideband of the 800 MHz I.O modulation, the 100 MHz signal is up converted to 6.4 GHz, a 64 times signal up-conversion. It is again reasonable to expect that with a 10 GHz modulator and 10 GHz I.O source, one can easily up convert a low frequency signal to 100 GHz and beyond, especially when this technique is combined with that proposed by C. Sun et al.^{5,6}

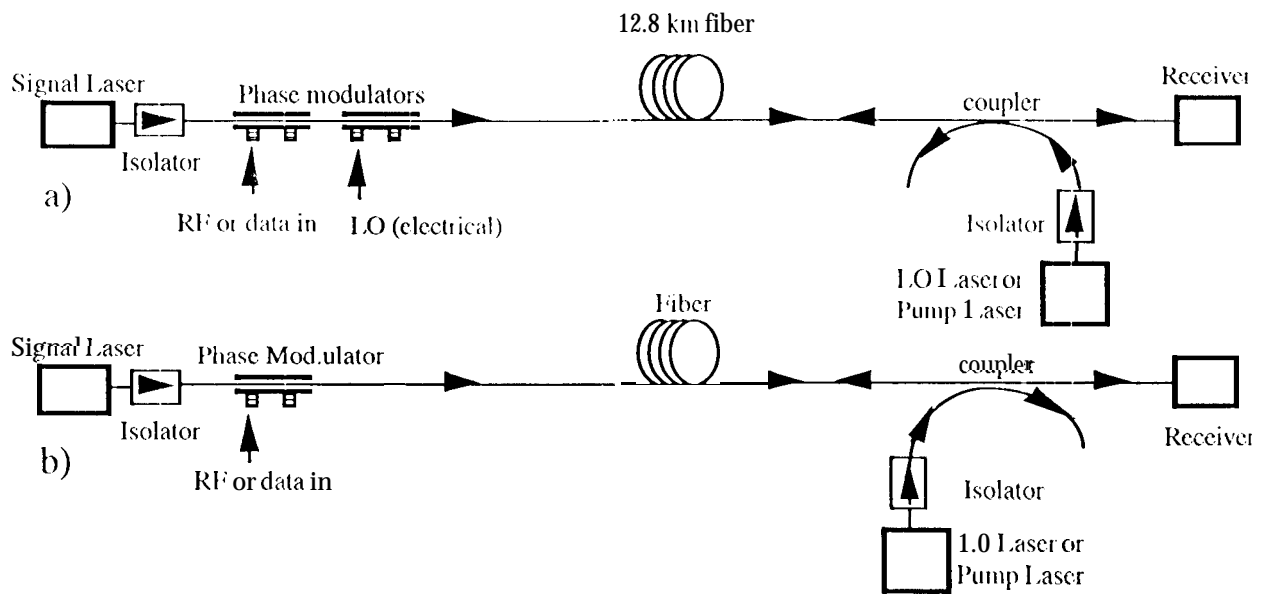


Fig. 9. a) Photonic mixing experimental setup. b) A typical coherent heterodyne communication link.

6. Phase and Frequency Locking in Coherent Heterodyne Systems

In a coherent homodyne or heterodyne communication link, a strong local oscillator is generally placed in front of the receiver to interfere with a phase modulated optical signal and convert it into an amplitude modulated signal, as shown in Fig. 9b. Since the local oscillator is much stronger than the original optical carrier of the signal, the receiving sensitivity will be greatly improved. One major obstacle preventing the coherent system from practical is the relative phase and frequency instability of the signal laser and the I.O laser.

Looking from a different angle, the photonic mixing configuration is essentially a coherent heterodyne system with the advantage that the I.O laser is automatically phase locked to the signal laser, as shown in Fig. 9a. Instead of directly sending the I.O laser signal into the photodetector like in a common heterodyne system, we send the I.O laser (the pump laser in Fig. 9a) towards the signal laser. Tuning the frequency of the I.O laser to one of the I.O modulation sideband, the sideband will be greatly amplified by the I.O laser via the Brillouin amplification process and go into the detector to beat with the signal sidebands. Because the phase and frequency of the amplified I.O sideband are derived from the signal laser and therefore are automatically locked to the signal laser, with a stability determined by the electrical I.O driving signal. On the other hand, most of the power of the amplified sideband comes from the I.O laser. Therefore, the I.O laser is indirectly phase locked to the signal laser through the seeded Brillouin amplification process.

7 Brillouin Opto-Electronic Oscillator

Using the powerful Brillouin selective sideband amplification concept, we successfully demonstrated an all optical Opto-Electronic Oscillator without using any electrical amplifier and filter and we termed such an OEO as Brillouin OEO. The elimination of the electrical amplifier in the OEO will make the device more compact and less power consuming. Perhaps more importantly, the elimination of the amplifier also eliminates the flicker noise associated with high frequency electrical amplifiers, resulting an OEO with lower phase noise. In addition, a phase modulator can be used in the Brillouin OEO to replace the amplitude modulator in a conventional OEO, eliminating the frequency drift associated with the bias drift of an amplitude modulator.

8. Other Applications

As described previously, Brillouin amplification has the disadvantages of narrow bandwidth and saturation induced nonlinearity. In all the applications described above, we successfully avoided these disadvantages by selectively amplifying a single tone. The beats of this amplified single tone with the carrier and other signal sidebands is the base for all the "tricks" used in the various applications.

In addition to the applications described above, Brillouin amplification can be used as a tunable filter with gain. With the Brillouin amplifier, one can selectively amplify any part of the RF spectrum by simply tuning either the frequency of the pump laser, the frequency of the signal laser, or RF carrier frequency. Such a tuning and amplification capability can be used in a broadcasting system, such as CATV, where each receiver has a pump laser so that each user can tune the frequency of the pump laser to select a channel. The same concept can also be used in frequency division multiplexing systems for signal demultiplexing. Finally, because of its agile tunability, the Brillouin amplifier should prove extremely useful in secure communication systems where the carrier frequency of the transmitter may hop rapidly. In order for a receiver to receive the correct data in such a system, it must be tuned synchronously with the transmitter. Armed with a key sequence for carrier frequency, a receiver equipped with a Brillouin amplifier is ideal for such a secure communication system.

SUMMARY

In summary, we have demonstrated the powerful concept of Brillouin selective sideband amplification. Such an amplification scheme is much more efficient than any other optical amplification schemes because all Brillouin scattering energy from the pump laser only goes into the needy weak sideband. Furthermore, because the strong carrier is not amplified, the saturation of the receiving photodetector can be avoided. Using the Brillouin selective amplification technique, we obtained a net link gain of 20 dB of an externally modulated photonic link at 5 GHz with an optical power of only 2.61 mW in the photodetector. Such a large and efficient signal amplification will prove extremely important in systems with narrow instantaneous bandwidth but broad overall bandwidth (e.g. widely tunable systems). It can also be used in an opto-electronic oscillator (OEO) to replace the bulky, power consuming, and costly RF amplifiers, resulting better performance with reduced size, power, and cost.

We also demonstrate broadband photonic signal up and down conversion with 12 dB gain by using Brillouin amplification. Such a demonstration makes photonic mixing readily applicable without having to employ high power lasers and high power photodetectors.

We further demonstrate using Brillouin amplification to convert phase modulation into amplitude modulation so that one can use lower loss phase modulators in photonic links to replace conventional Mach-Zehnder modulators. Such a replacement not only results in much higher link gain, but also eliminates the bias drift associated with biasing the Mach-Zehnder modulators. In addition, the Brillouin amplification can also turn a phase modulator into an efficient photonic frequency multiplier with large multiplication factors, without having to overly drive the modulator nor to use high power lasers. This makes the photonic frequency multiplication practical.

We believe that Brillouin amplification will open many opportunities for the research and development of microwave photonic systems and devices in the time to come.

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. We thank John Dick, W. Shieh, and G. Lutes for helpful discussions.

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The research described in this presentation was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.



Outline of the Presentation

- 1) Problems to solve
- 2) Brillouin scattering & its properties
- 3) Powerful selective sideband amplification concept
- 4) Brillouin sideband amplification experimental results
- 5) Advantages & Limitations
- 6) Applications
 - i) Single tune amplification
 - ii) FM & PM communication with agile tunability.
 - iii) Photonic signal up & down conversion with gain
 - iv) PM to AM conversion
 - v) Simultaneous signal mixing and multiplication with gain
 - vi) Frequency multiplication & frequency comb generation
 - vii) Brillouin Optoelectronic Oscillator
- 7) Summary



Problems to Solve of Photonic Microwave Systems

1) High E/O and O/E conversion loss

To lower the conversion loss

- ==> High power laser

- ==> High cost

- ==> High Power Detector

- ==> Harmful Stimulated Brillouin Scattering (SBS)

- ==> High power electrical pre-amplifier

- ==> Large power w I w @ e R -

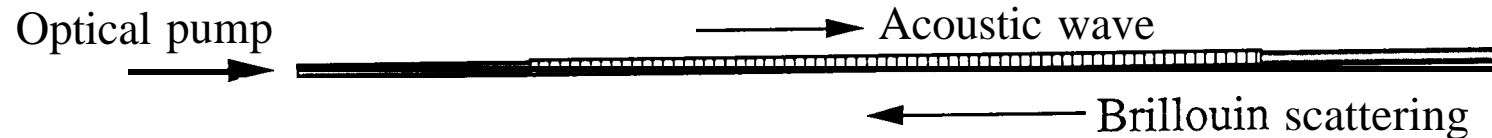
- ==> Nonlinearity

2) Bias drift of external modulator

* Brillouin Amplification can solve both problems

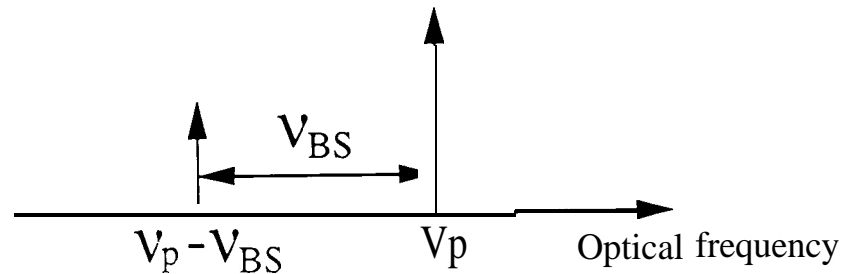


Brillouin Scattering & Its Properties



Optical field $\xrightarrow{\text{Piezoelectric effect}}$ electrostrictive strain \Rightarrow acoustic grating
 $\xrightarrow{\text{acousto-optic effect}}$ diffract optical wave \Rightarrow Brillouin scattering

$$v_{BS} = \frac{2nv_A}{\lambda_p}$$



Properties:

- 1) Narrow line width: ~ 10 MHz
- 2) For 1300 nm pump, $v_{BS} \sim 13$ GHz. For 1550 nm pump, $v_{BS} \sim 10$ GHz
- 3) Extremely efficient

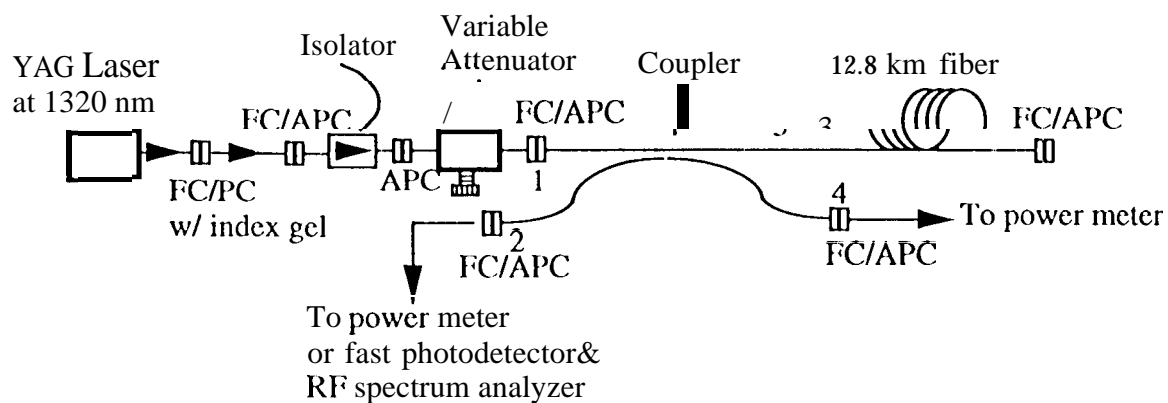


Fig. 1. Stimulated Brillouin Scattering Measurement Setup

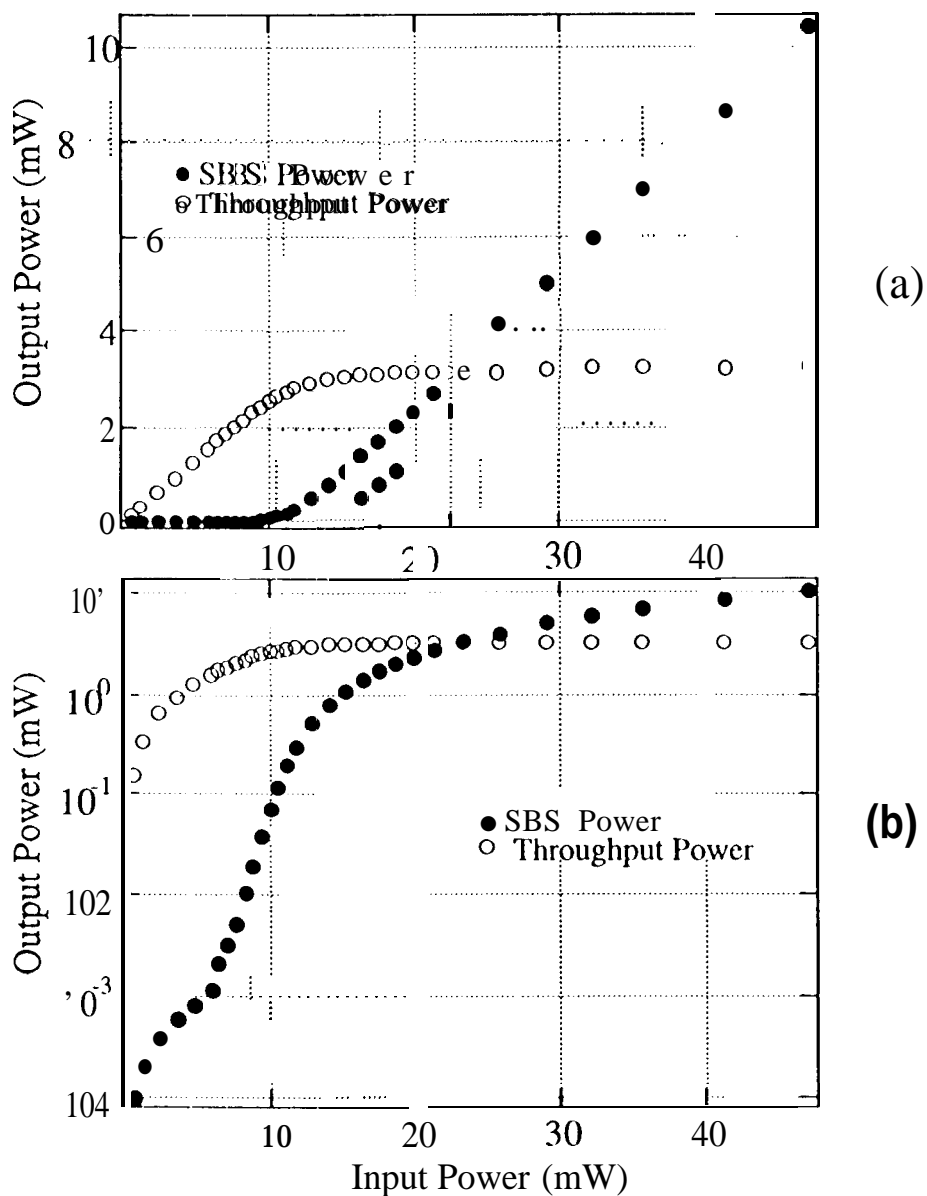
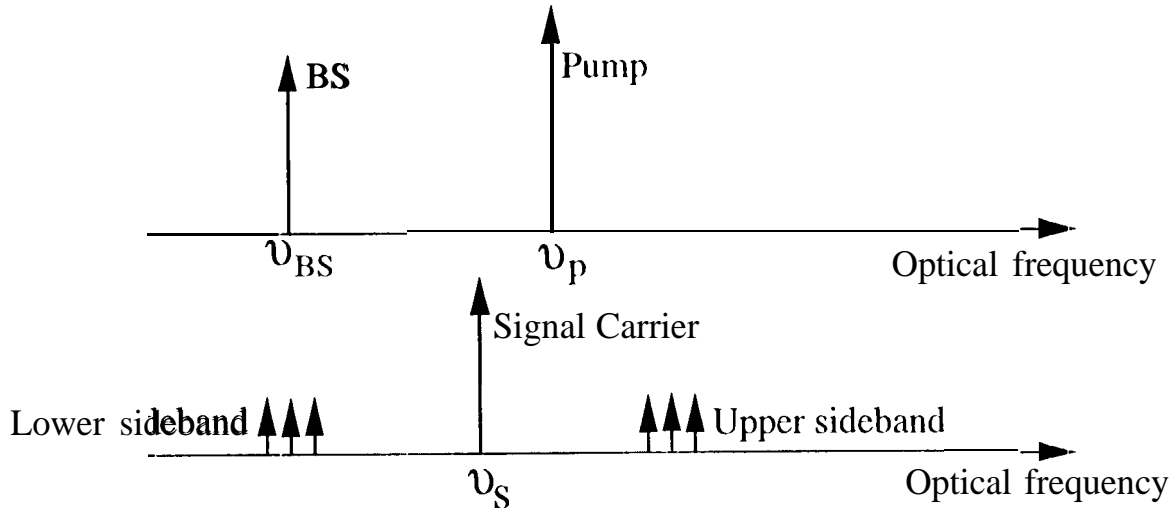


Fig. 2 Measurement of Brillouin scattering power and throughput power



The concept of selective sideband amplification



Advantage:

only amplifies the needed

==> Efficient

==> No photodetector saturation

==> No need to drive modulator hard

==> Increasing modulation depth

Fig. 2

Brillouin Selective Sideband Amplification Setup

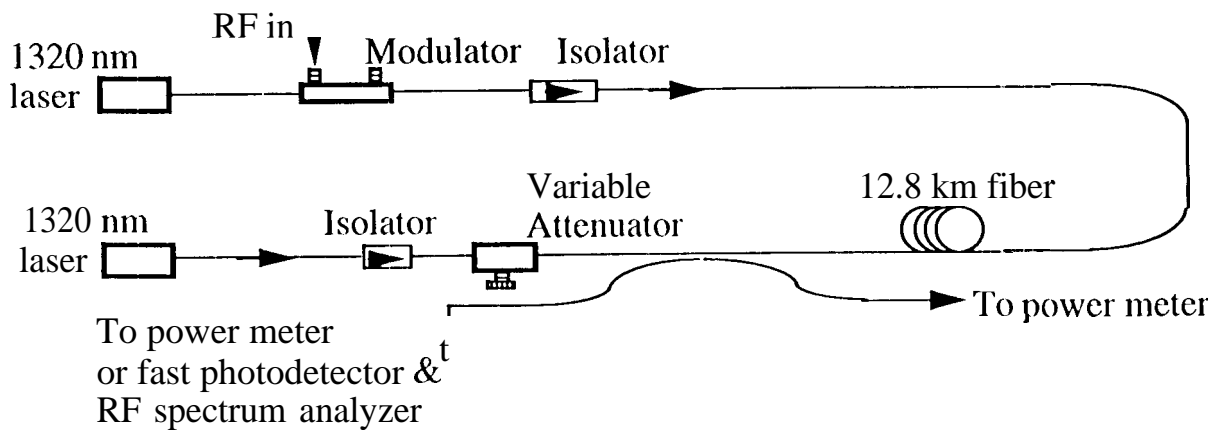


Fig. 1

Beating SBS w/ Pump

Span: 100 MHz, RBW: 10 kHz

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RF Beat Power (dBm)

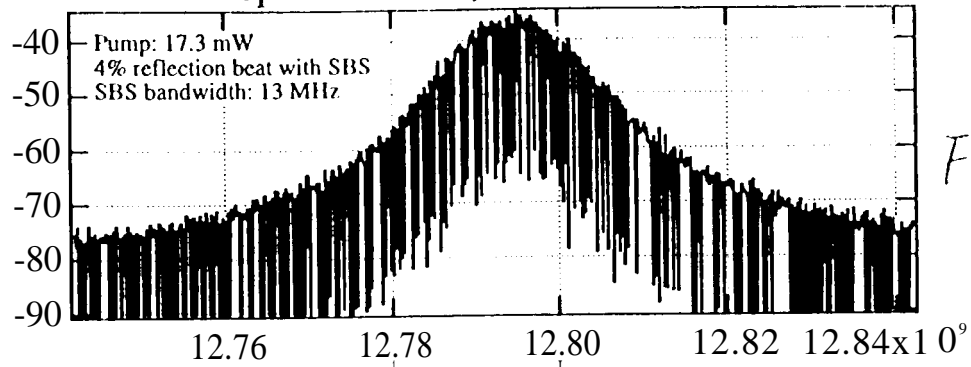


Fig. 3a

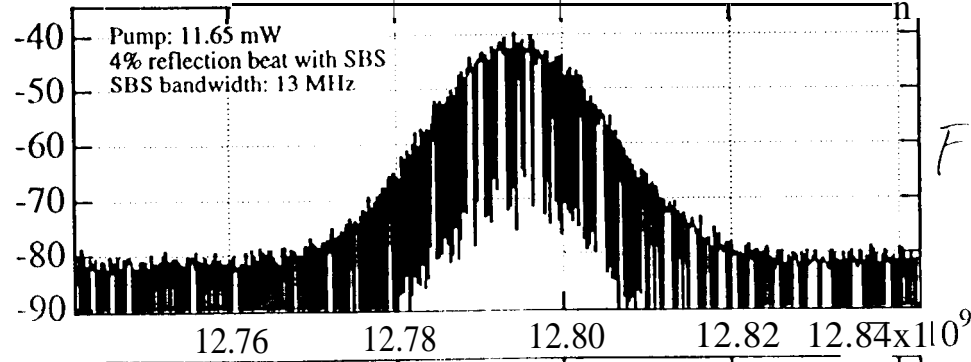


Fig. 3b

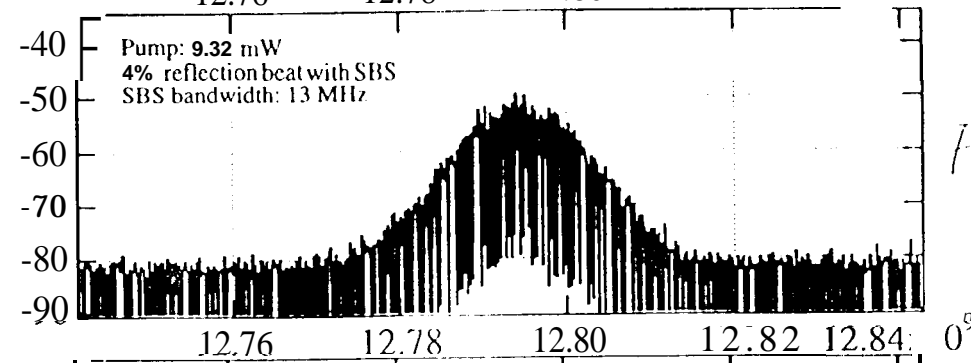


Fig. 3c

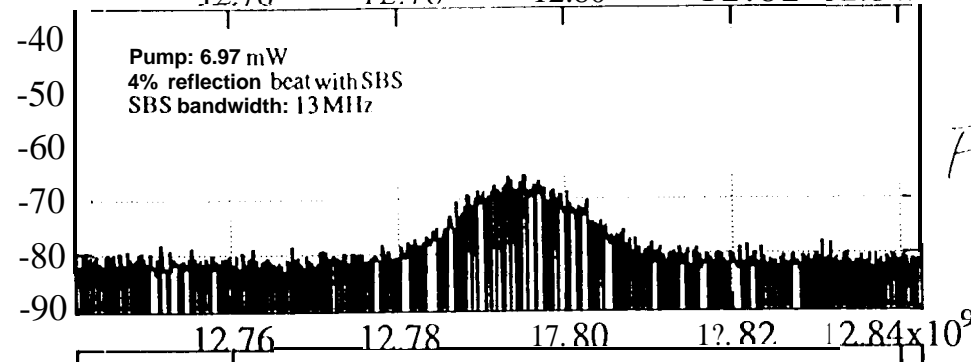


Fig. 3d

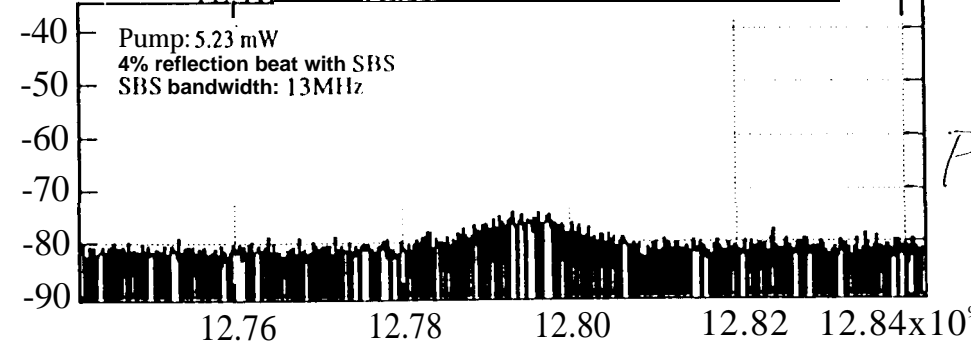
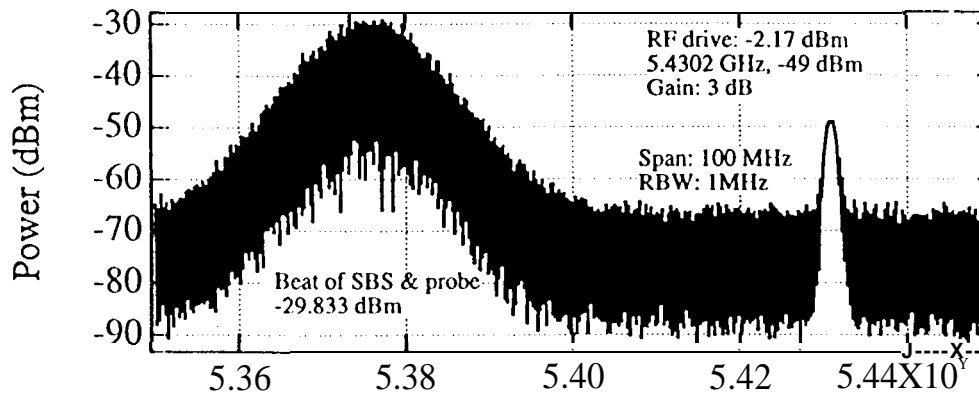
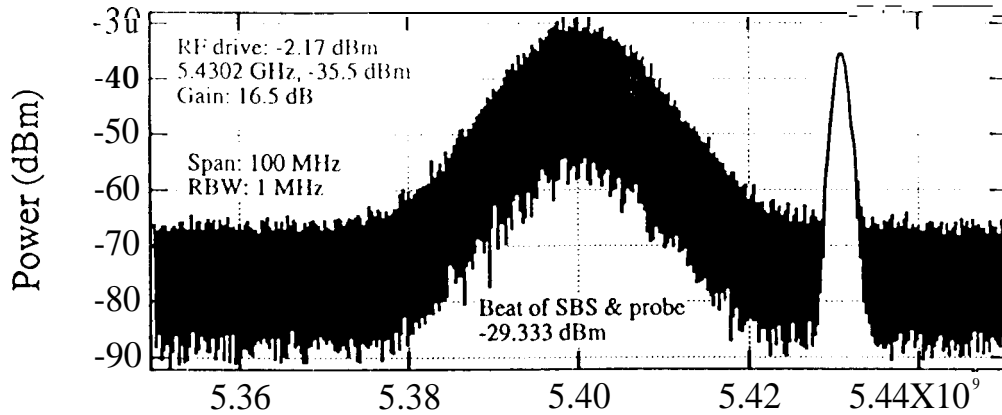
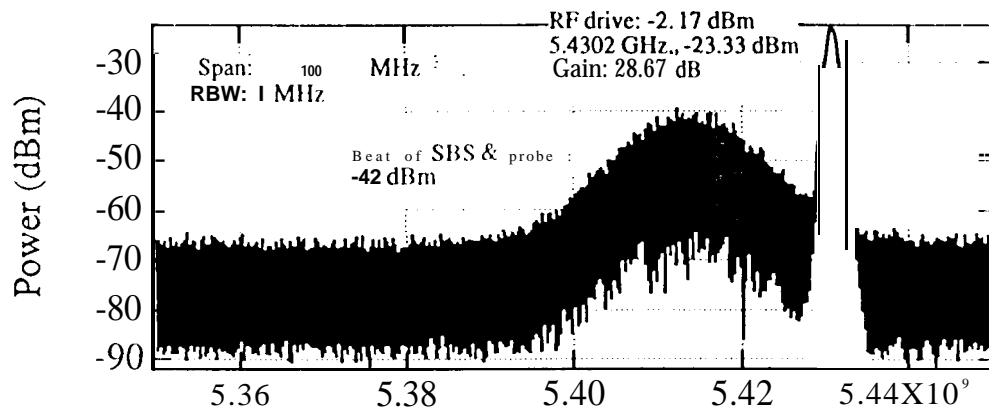
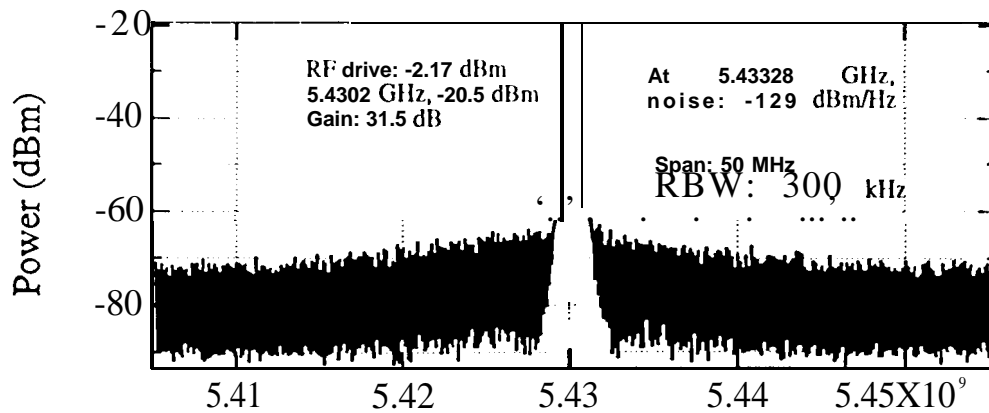


Fig. 3e

Frequency (Hz)

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SBS Amplification vs. Probe Frequency



Frequency (Hz)

1 0/22/96

SBS Signal Amplification

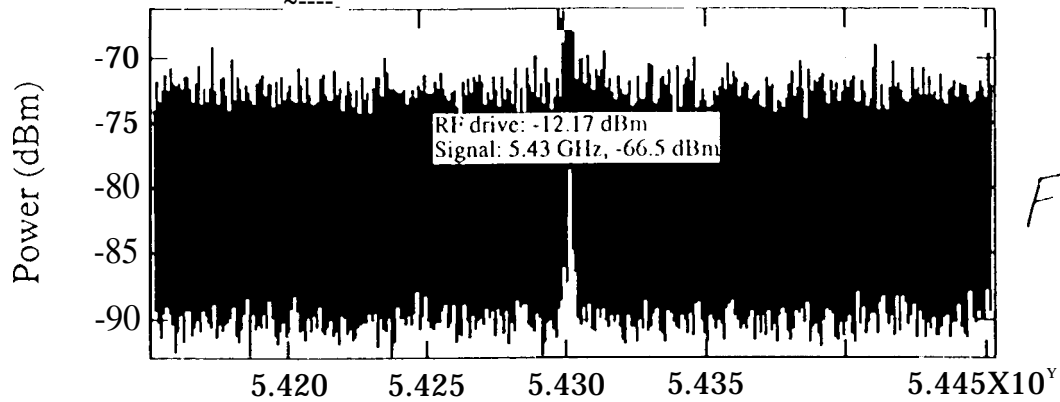


Fig 7a

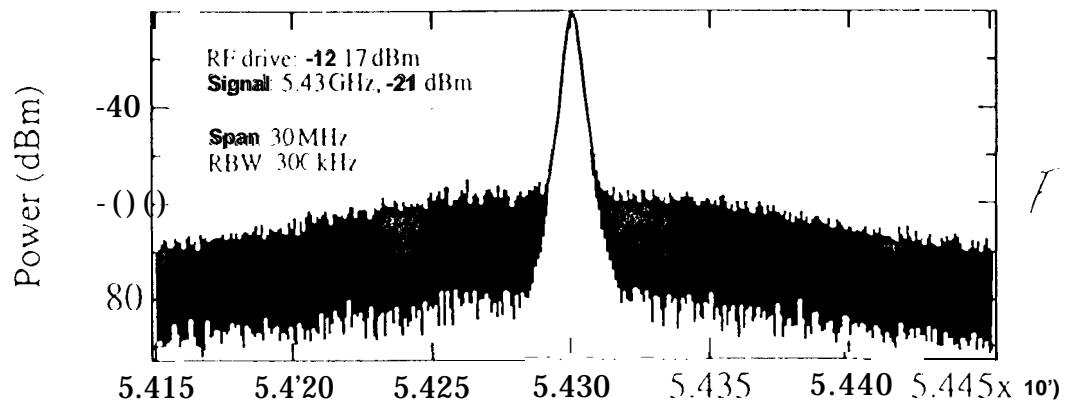


Fig 7b

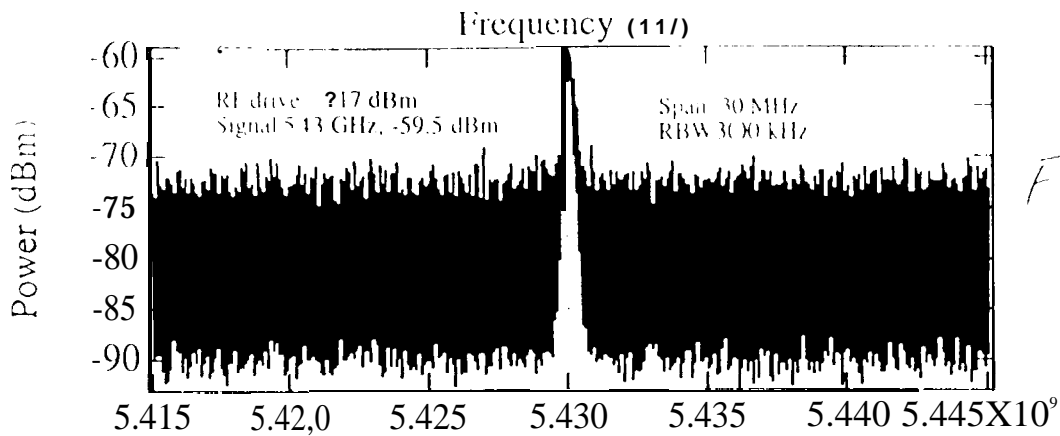


Fig. 8a

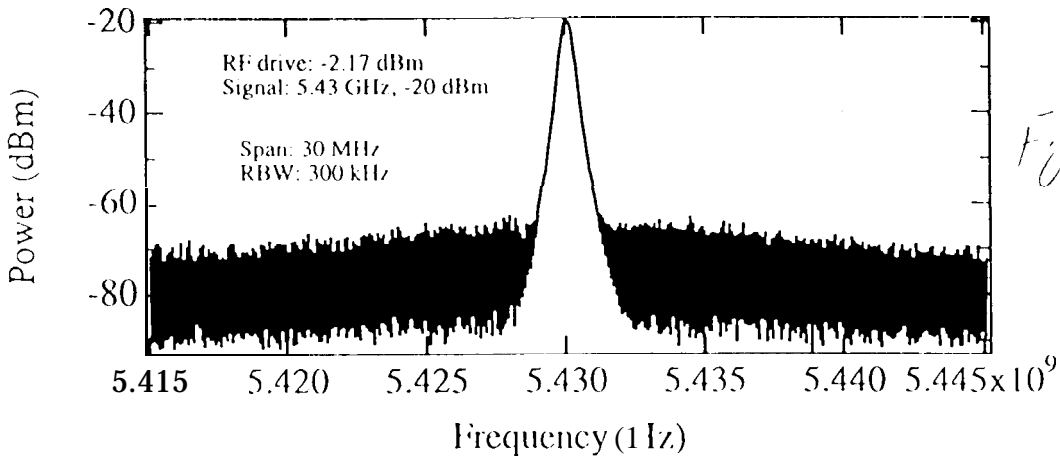


Fig 8b

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RF Gain vs. Optical Pump Power

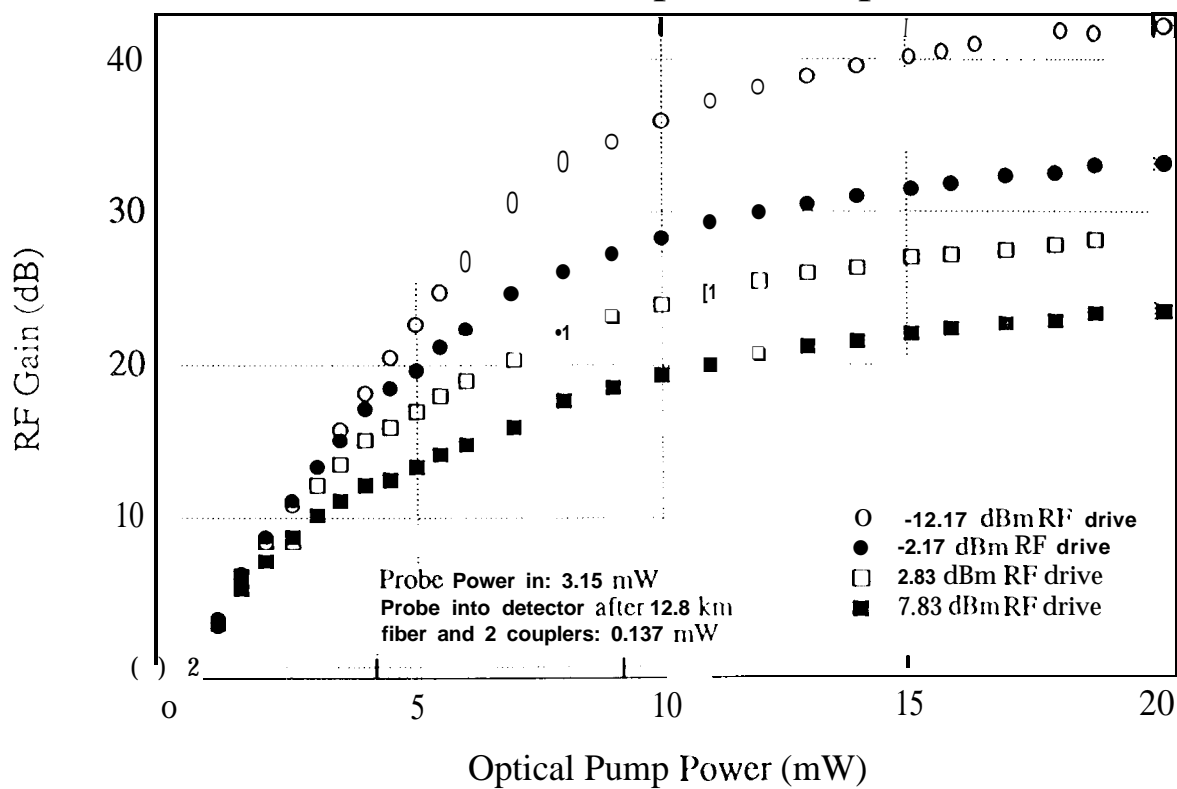


Fig. 12

Fig. 12

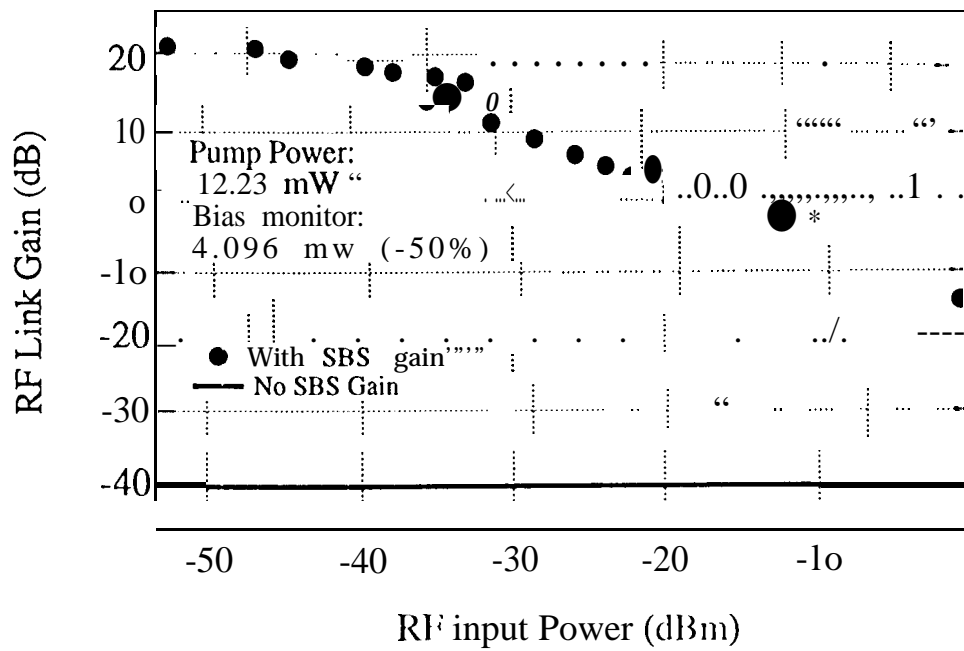


Fig. 13 RF link gain with and without SBS amplification as a function of RF input power

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Amplified Signal vs. RF Driving Power

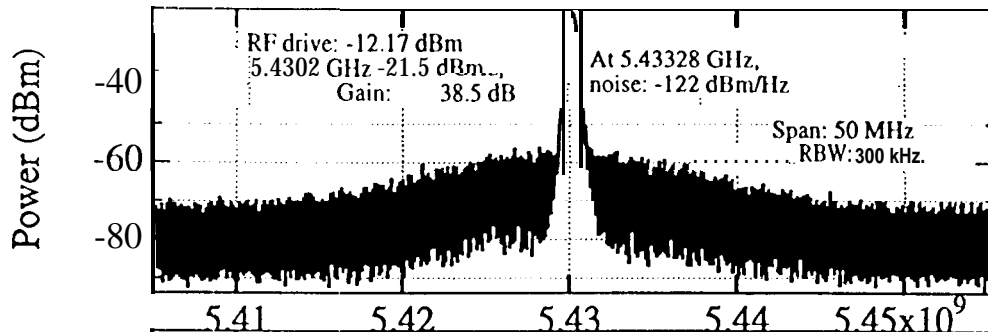


Fig. 9a

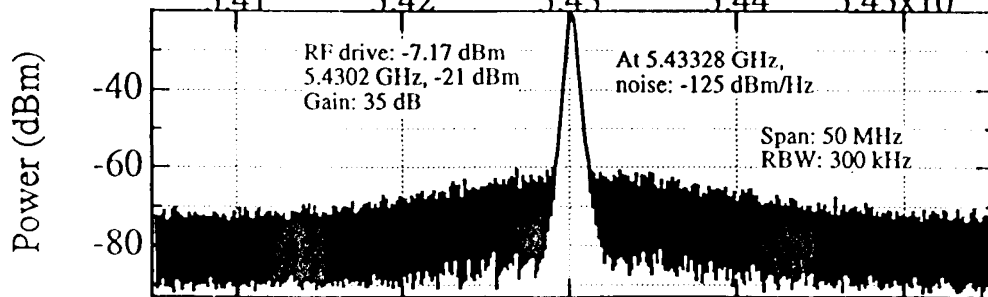


Fig. 9b

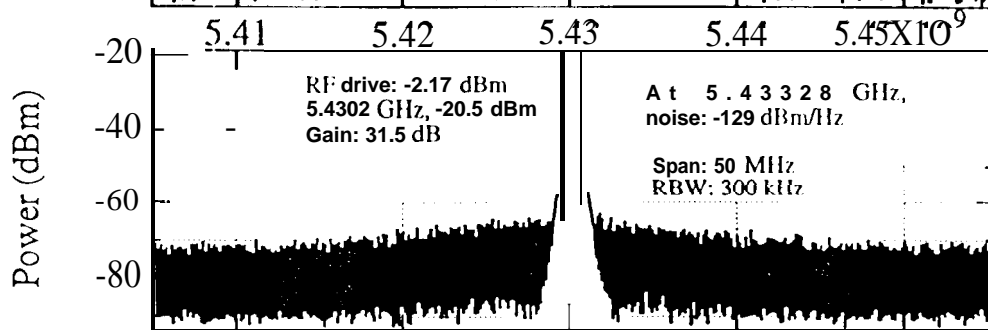


Fig. 9c

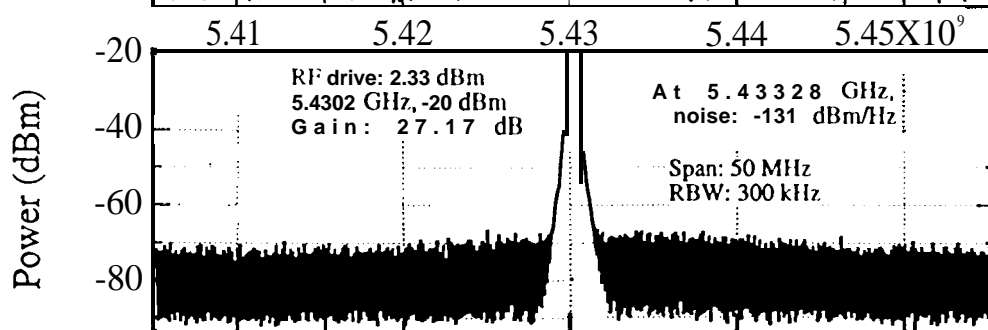


Fig. 9d

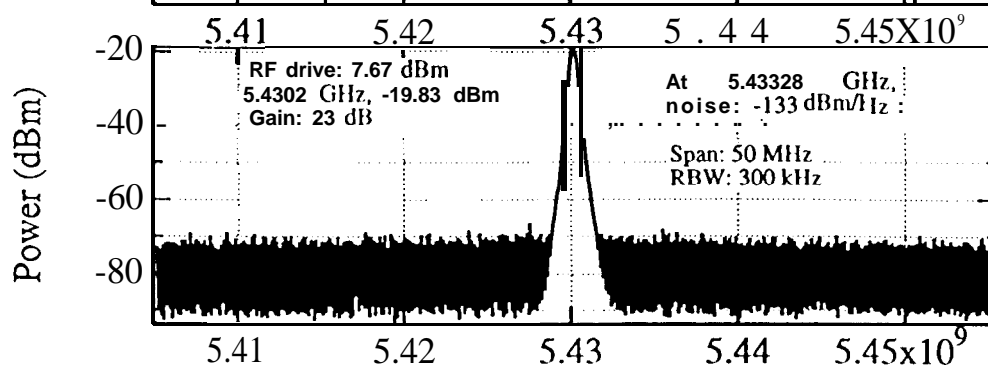


Fig. 9e

Frequency (Hz)



Limitations & Advantages

Limitations

1. Narrow instantaneous bandwidth
==> No good for digital communication
2. Relatively high amplifier noise at low signal level
==> May decrease SIR.
3. Low saturation
==> May cause intermodulation distortion for AM systems.

Advantages

1. Narrow instantaneous bandwidth
==> Selective sideband amplification
2. Wide overall bandwidth
==> For widely tunable systems
3. Agile tunability
==> For FDM systems as a tuner with amplification.
4. High efficiency
==> Only amplifies the needy, less power consumption.

A lot of applications in which we can

Get around these limitations

Take these advantages

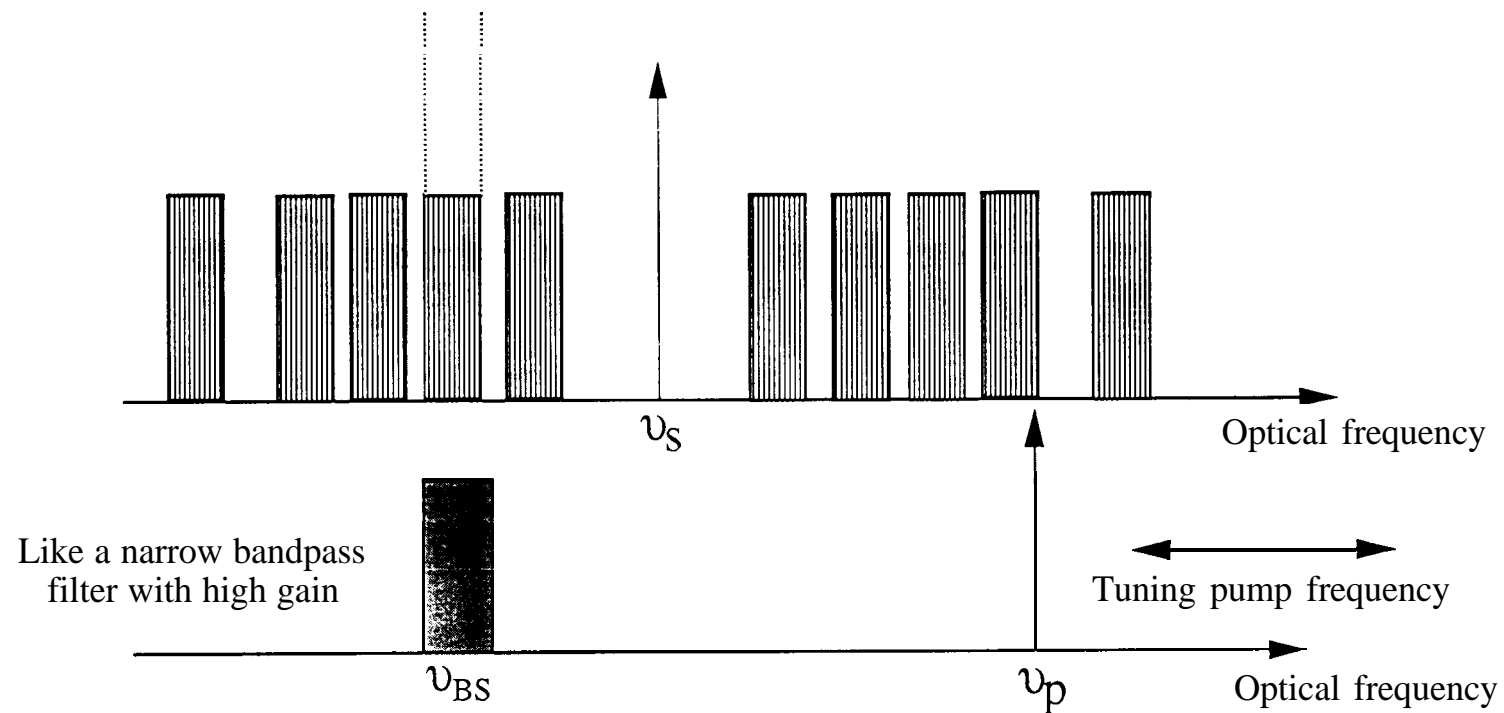


Applications of Brillouin Amplification

1) Amplifying a single tone, such as an LO signal.

==> No worry of internodulation distortion.

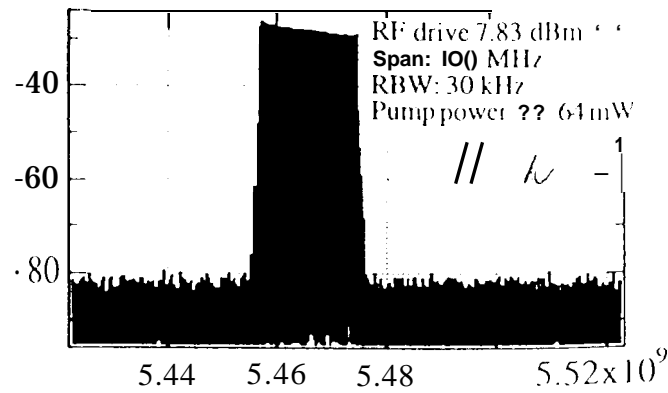
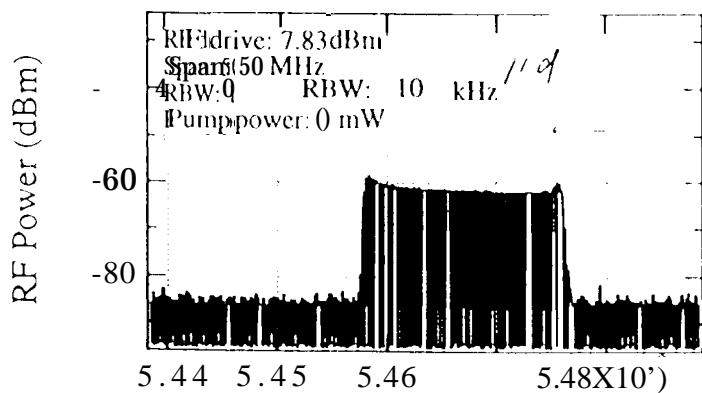
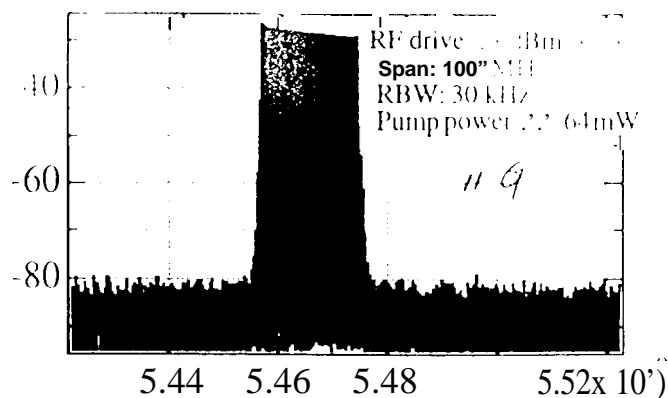
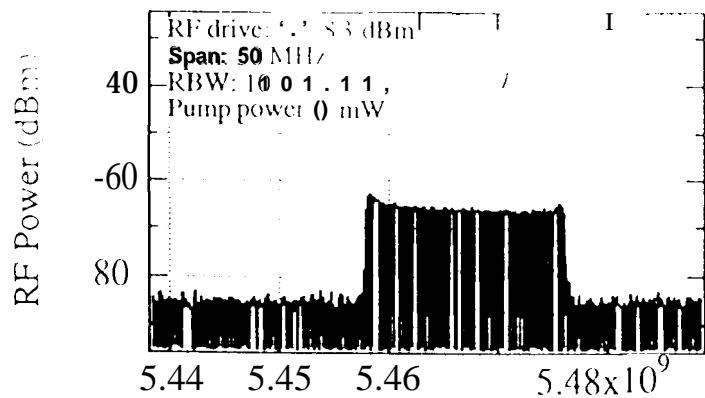
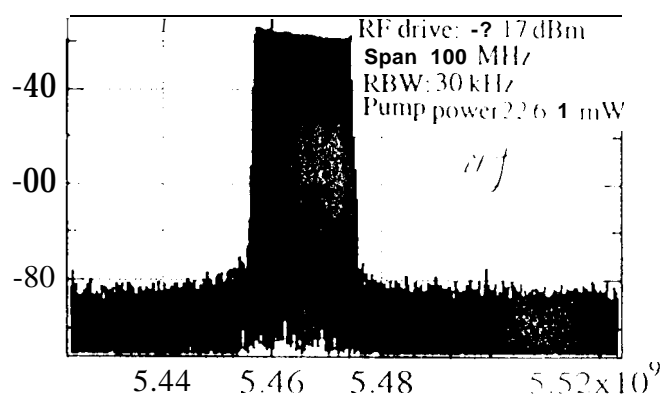
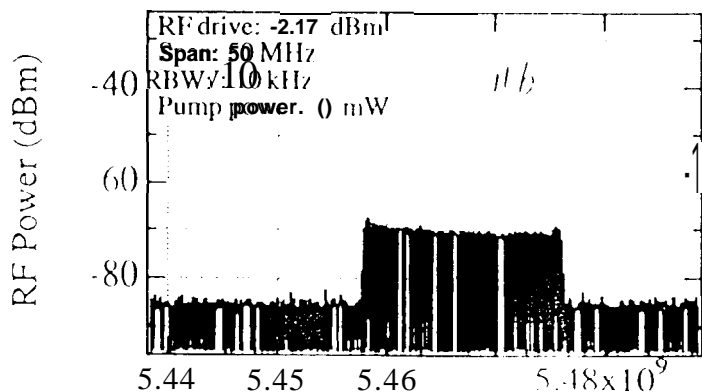
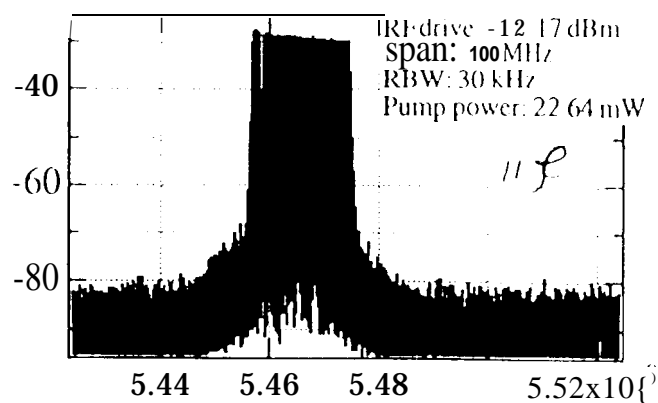
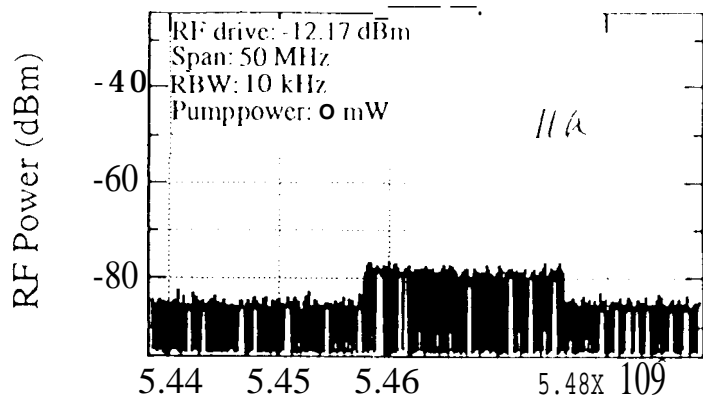
2) Tuner for FM Frequency Division Multiplexing systems or frequency hopping systems.



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FM signal w/out amplification

FM signal with amplification



Frequency (Hz)

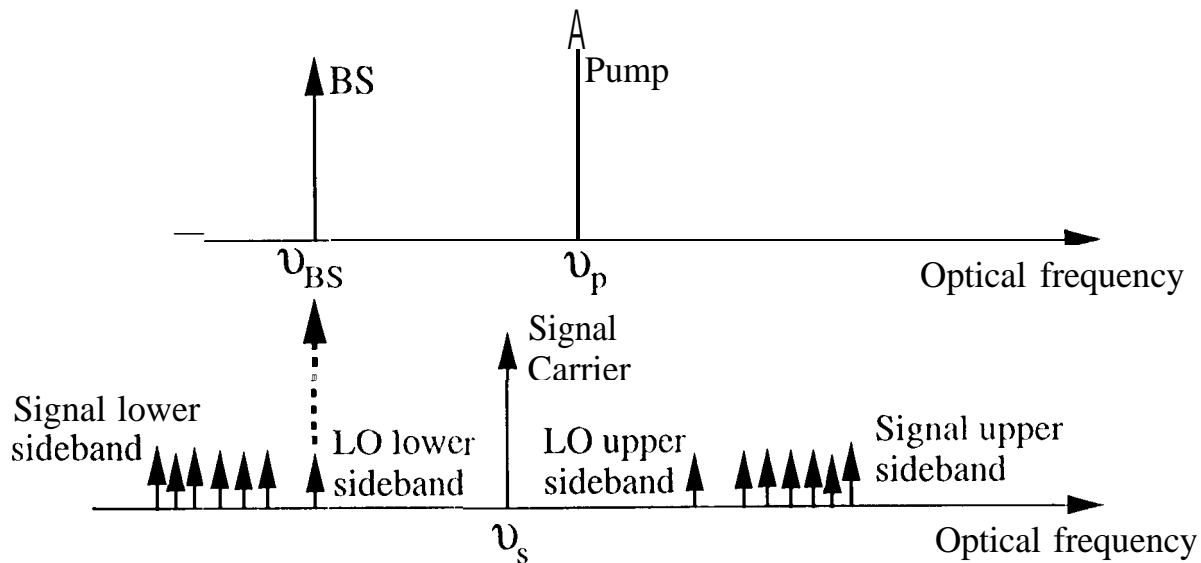
Frequency (Hz)



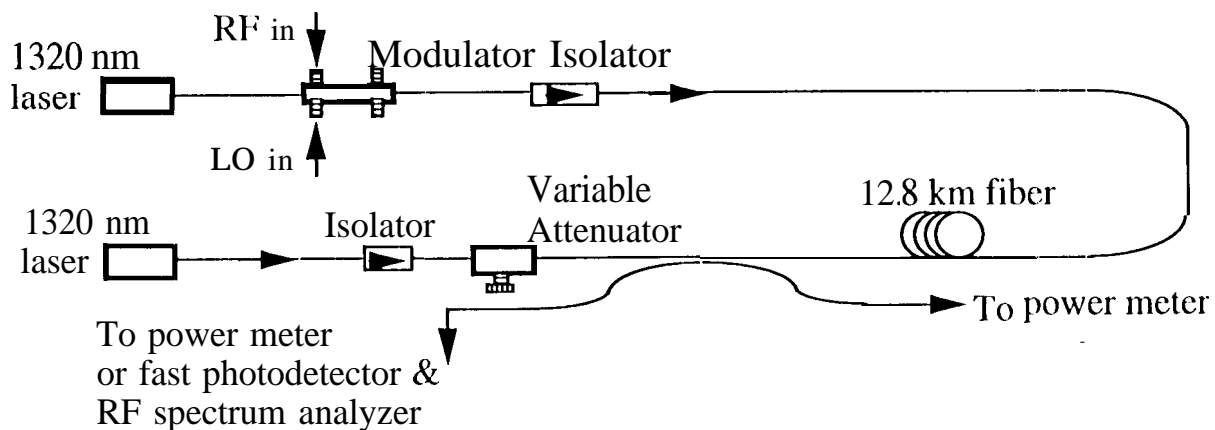
Applications of Brillouin Amplification

3) Signal up & down conversion

For both wide & narrow bandwidths and for both FM & AM systems.

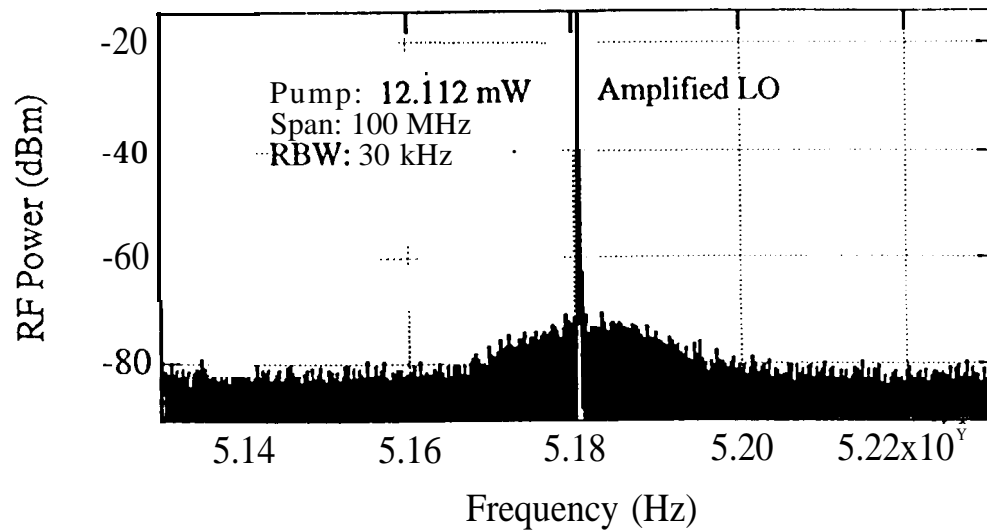
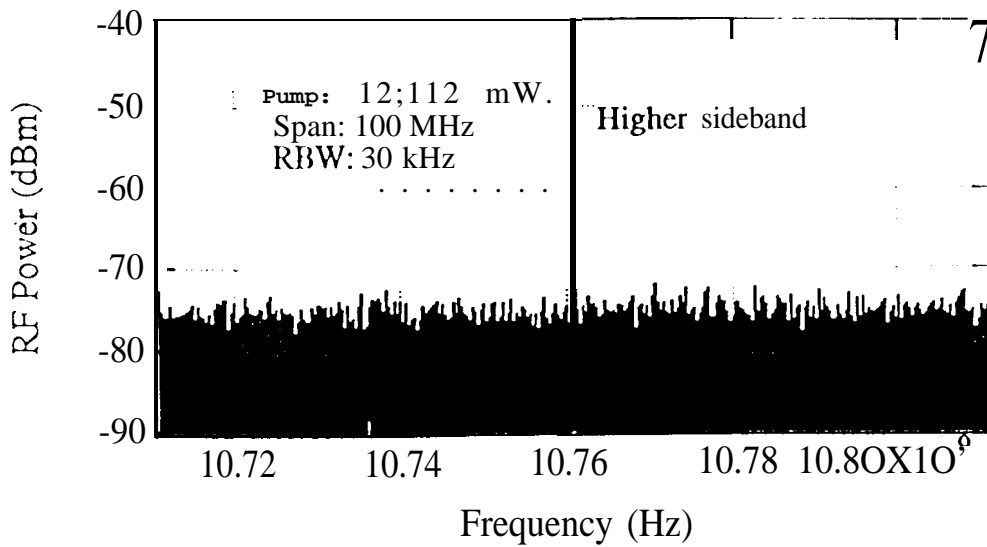
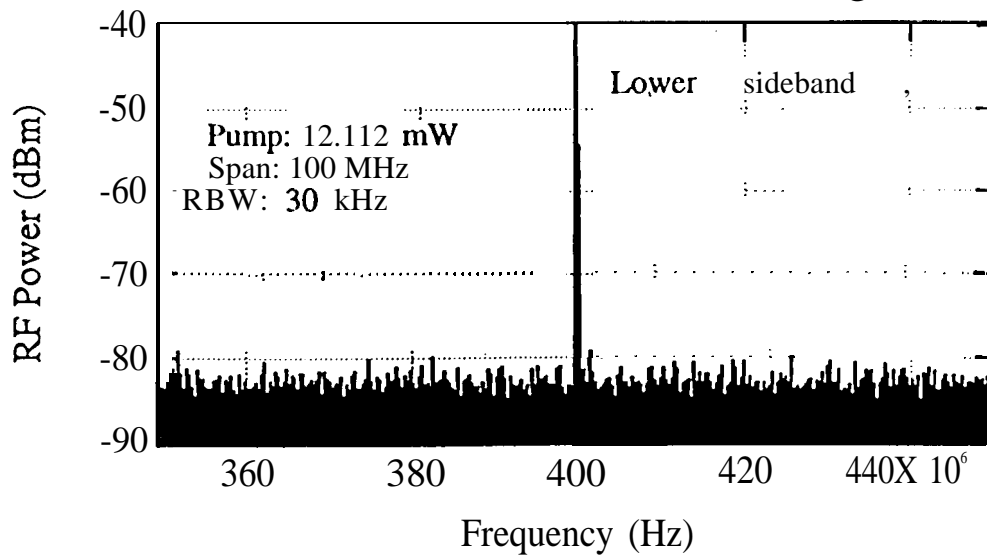


Demonstrating Photonic Mixing with Brillouin Gain



SBS Assisted Photonic Mixing

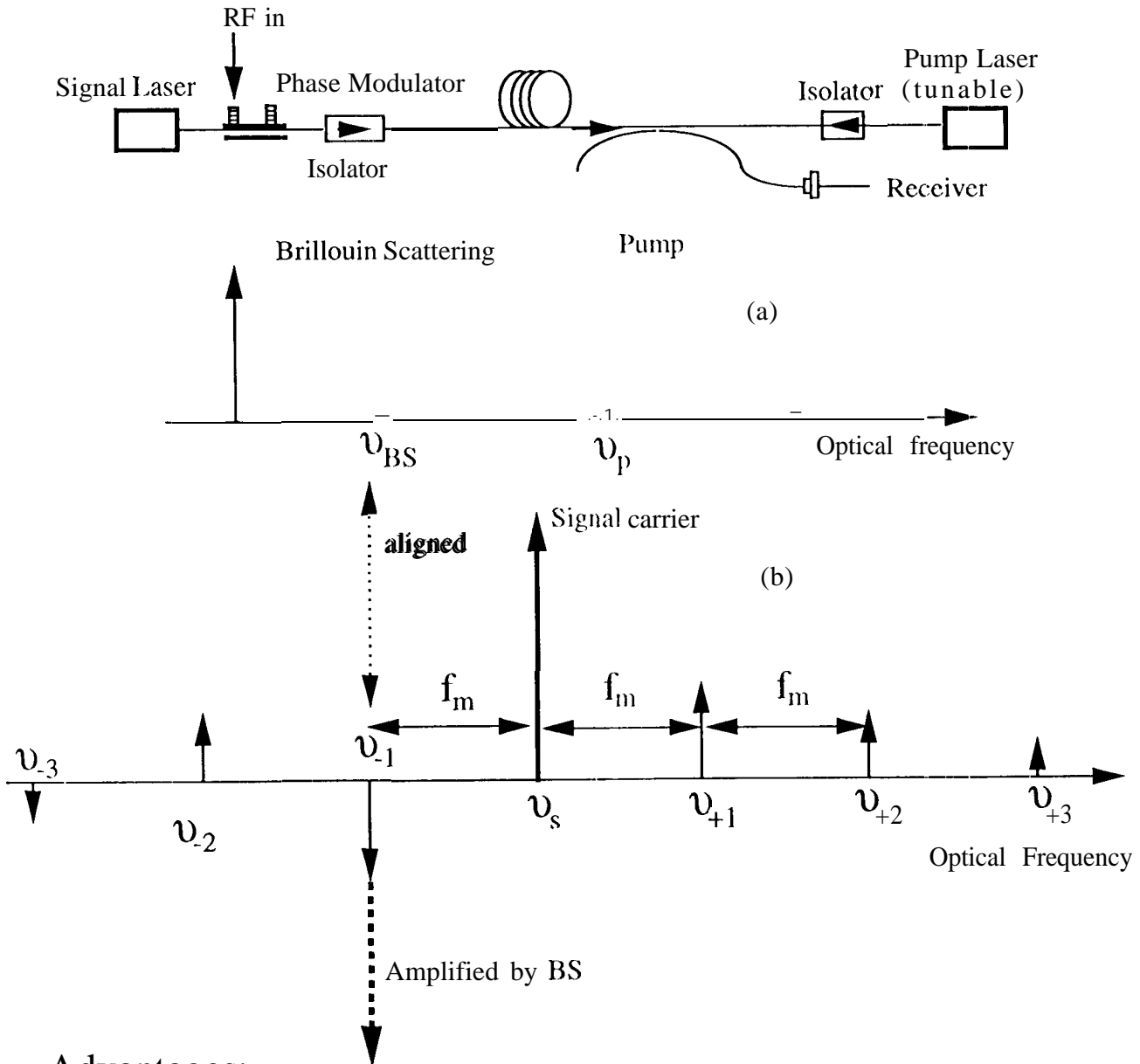
11/1/96





Applications of Brillouin Amplification

4) PM to AM conversion by selective Brillouin amplification



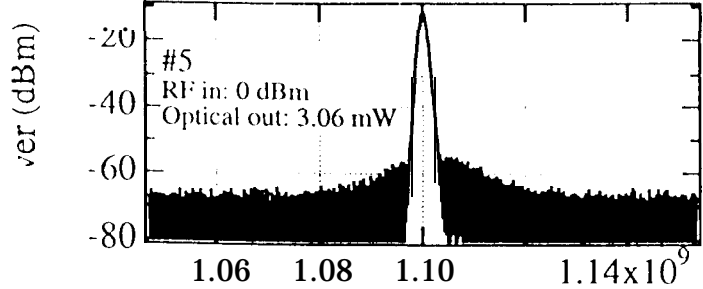
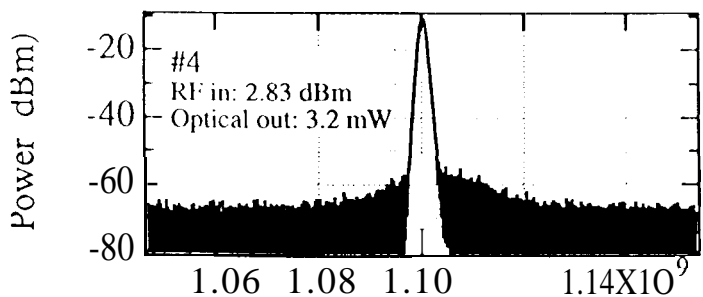
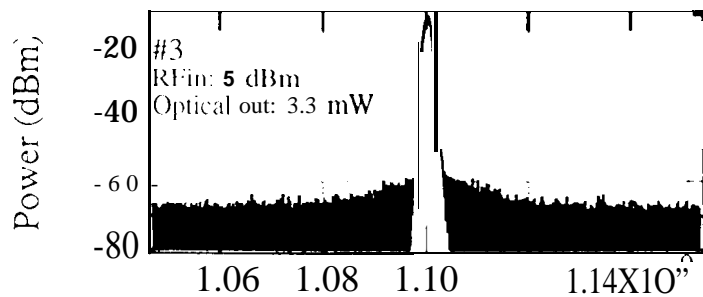
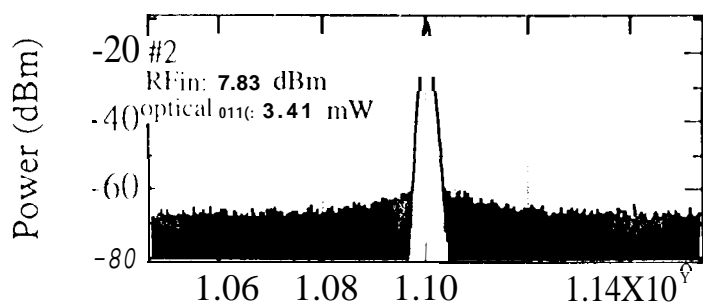
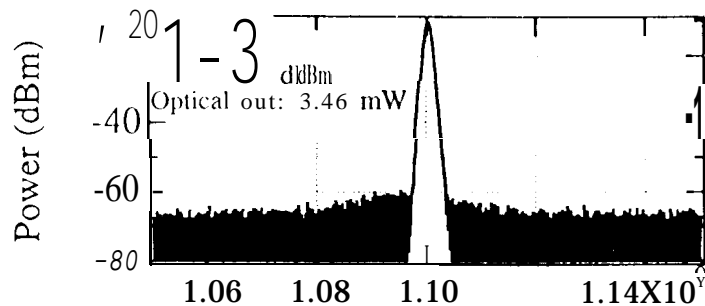
Advantages:

- * Lower loss by at least 3 dB.
- * No bias \implies No bias drift.
- * Lower cost

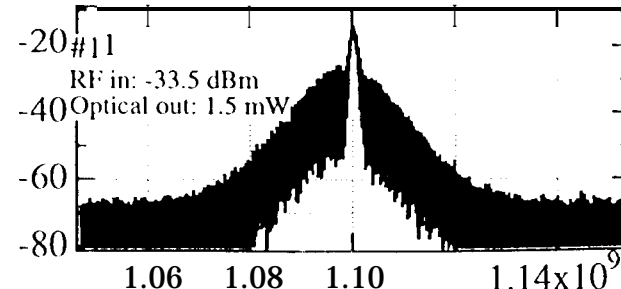
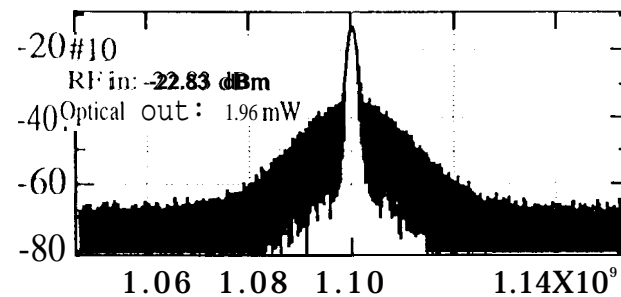
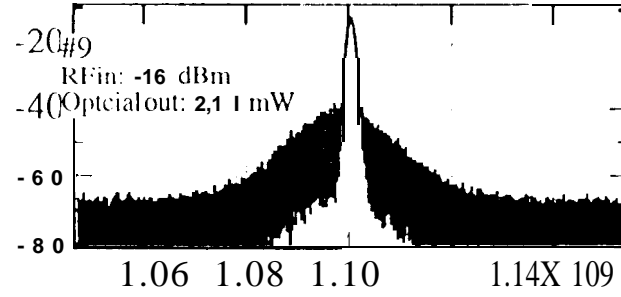
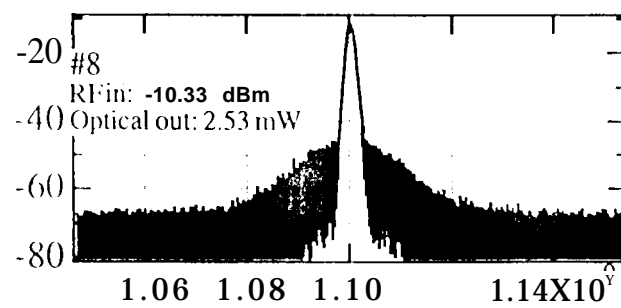
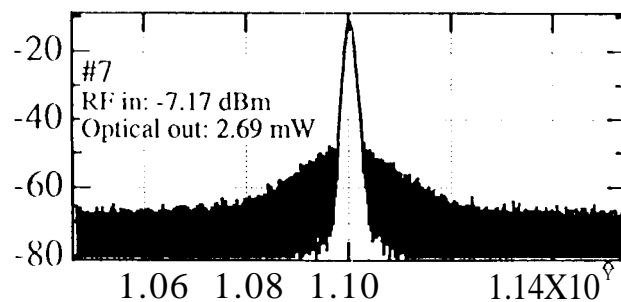
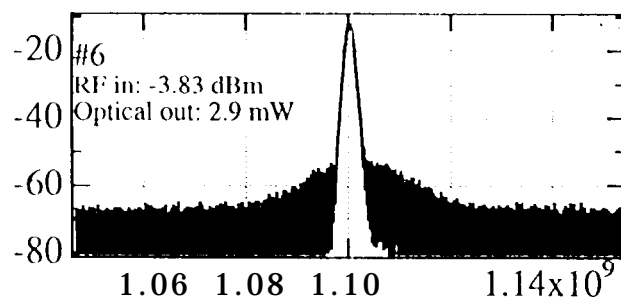
12/1 0/96

PM to AM conversion with Brillouin Amplification

(Span:100MHz, RBW: 1 MHz, Pump Power: 11,8 mW,
0.55mW Optical output without Brillouin amplification)



Frequency (Hz)

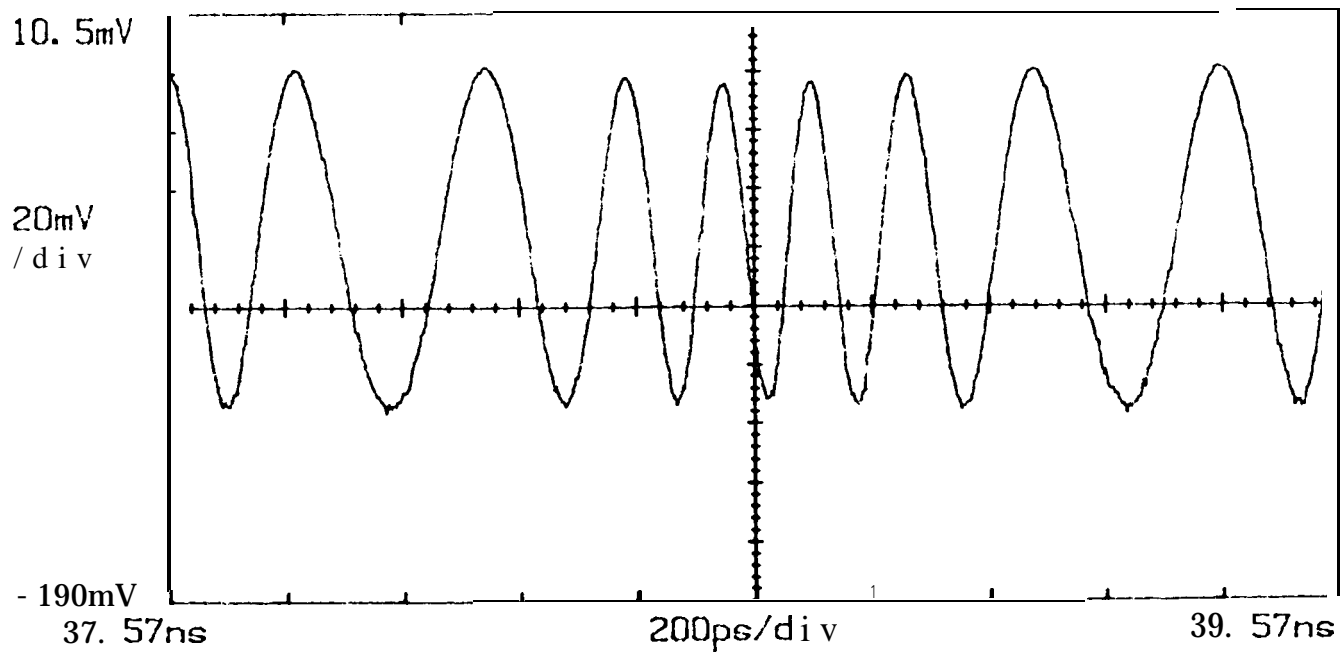
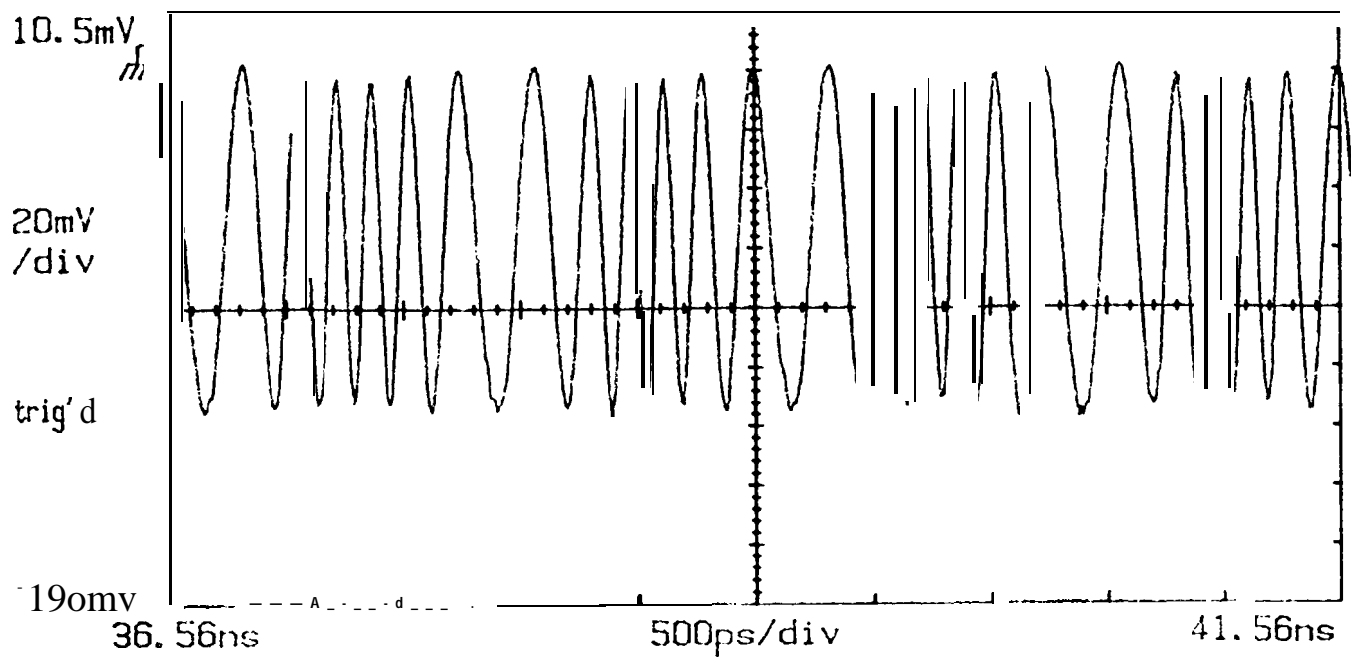


Frequency (Hz)

12/30/96 10:53:15

CSA803 COMMUNICATIONS SIGNAL ANALYZER

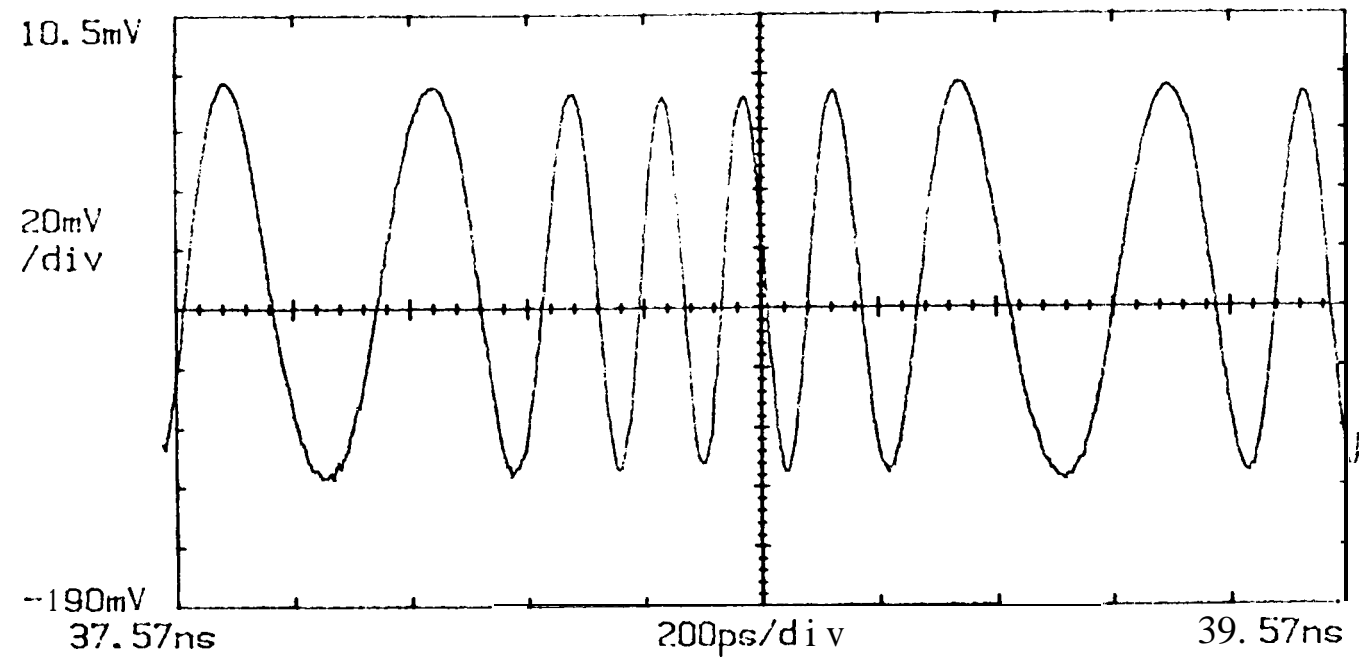
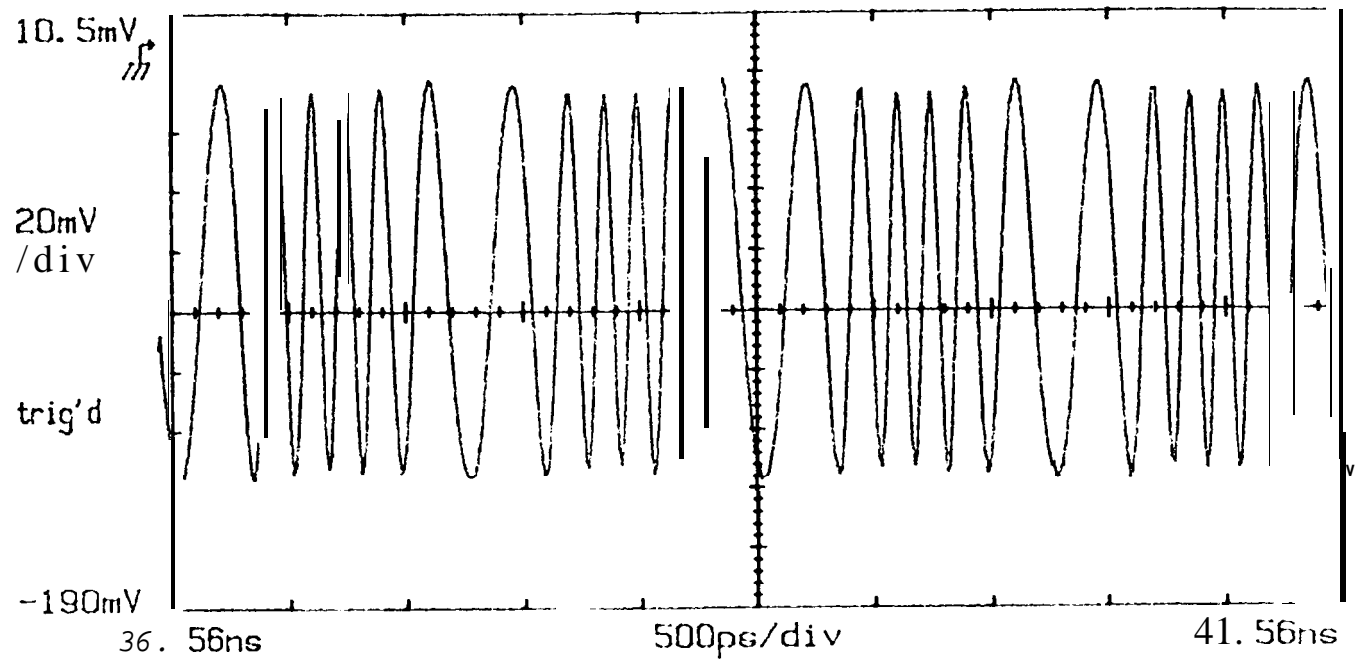
date: 30-DEC-96 time: 18:41:01



12/30/10 *y=111* *highly non harmonic*

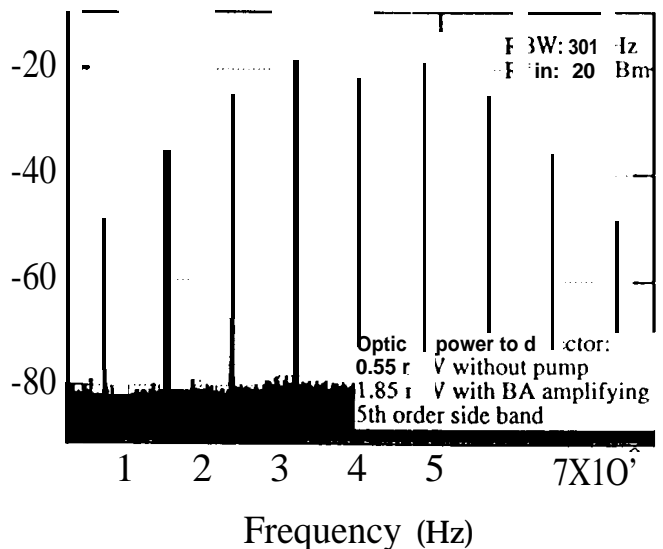
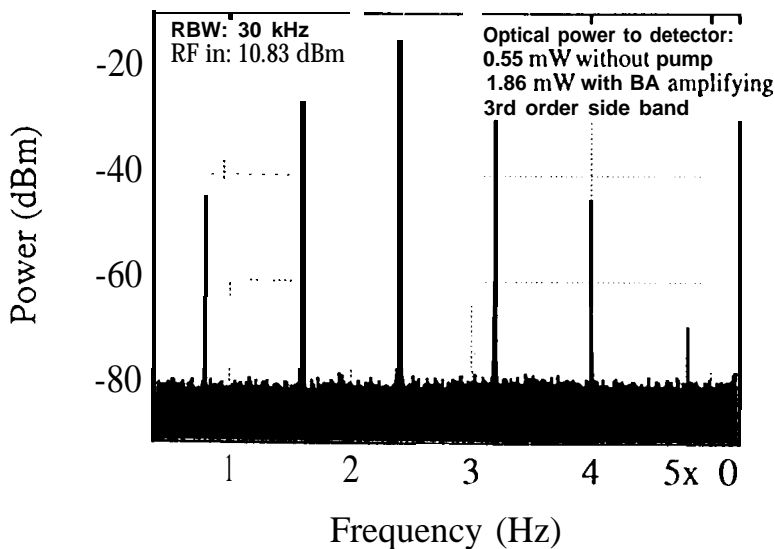
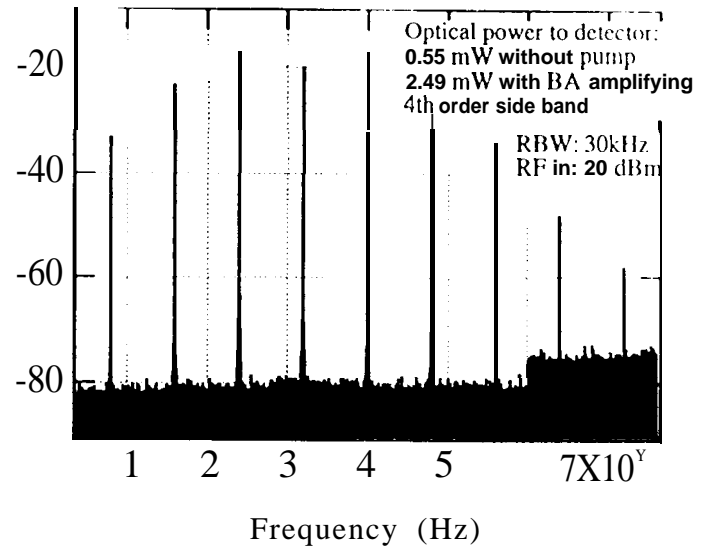
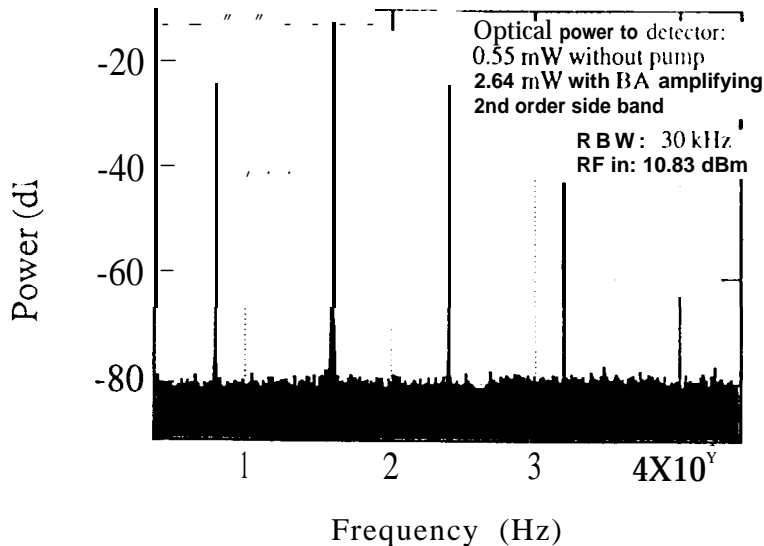
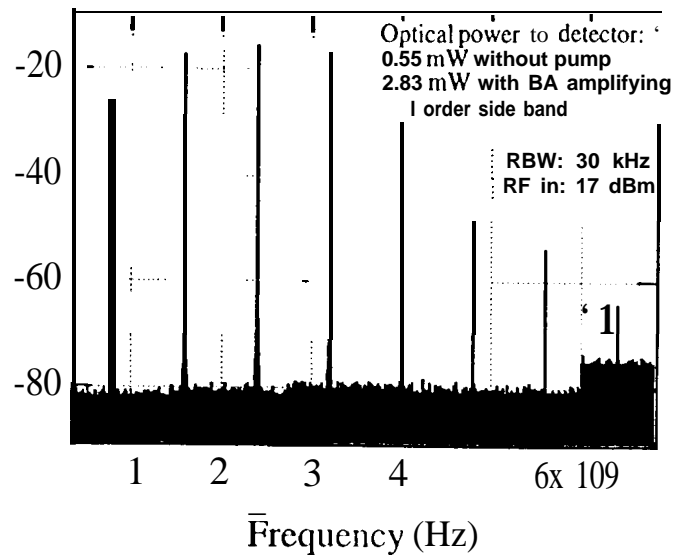
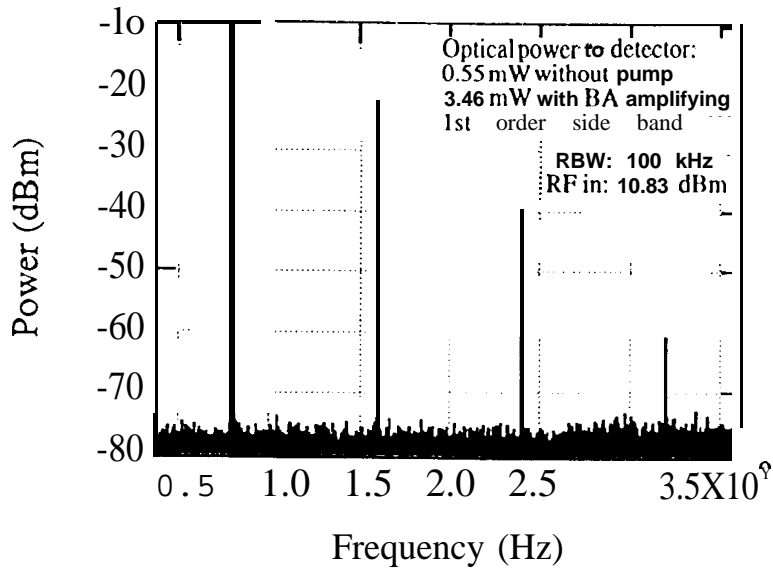
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date: 30-DEC-96 time: 18:32:44



Frequency Multiplication using Brillouin PM to AM Conversion

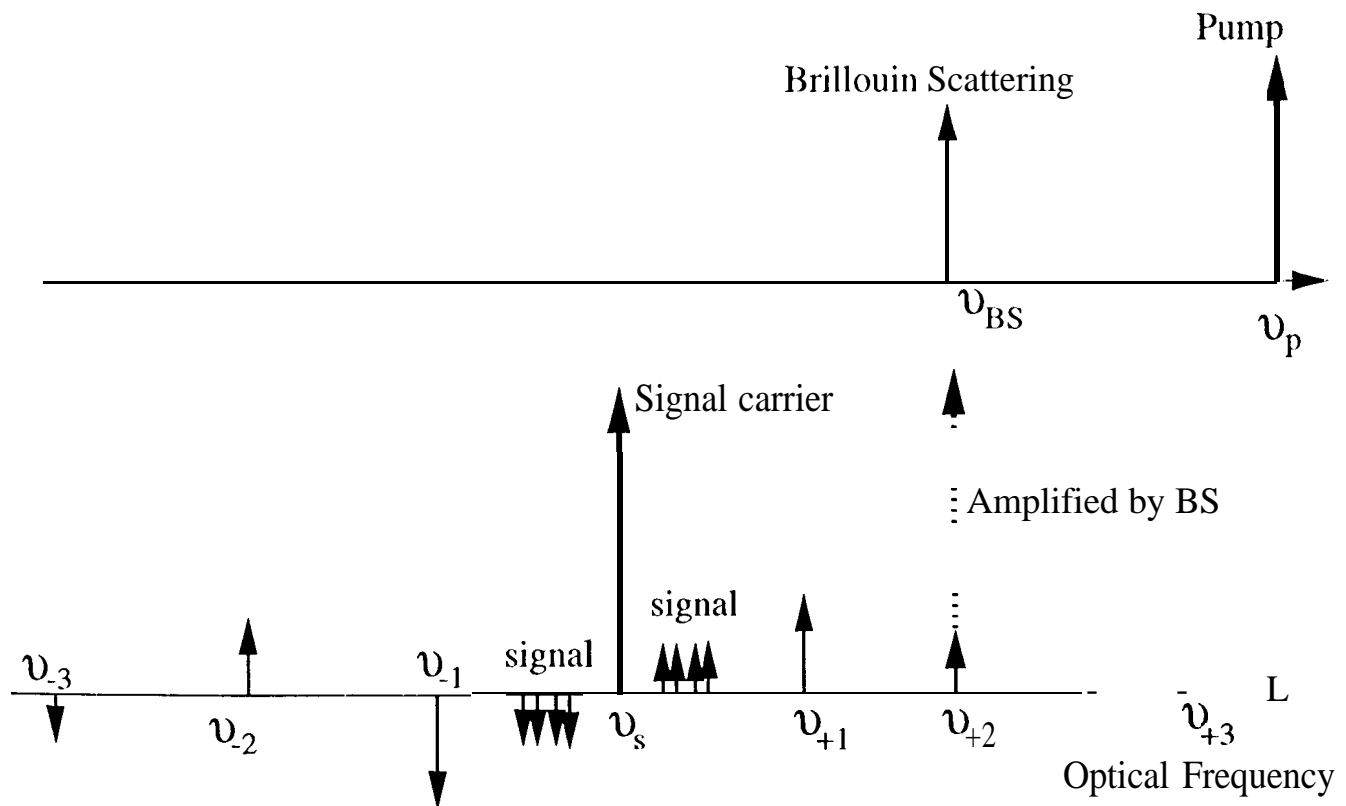
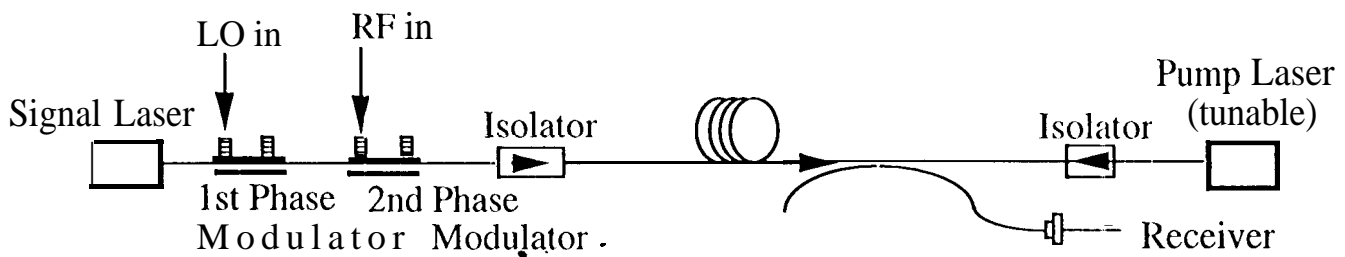
12/10/96



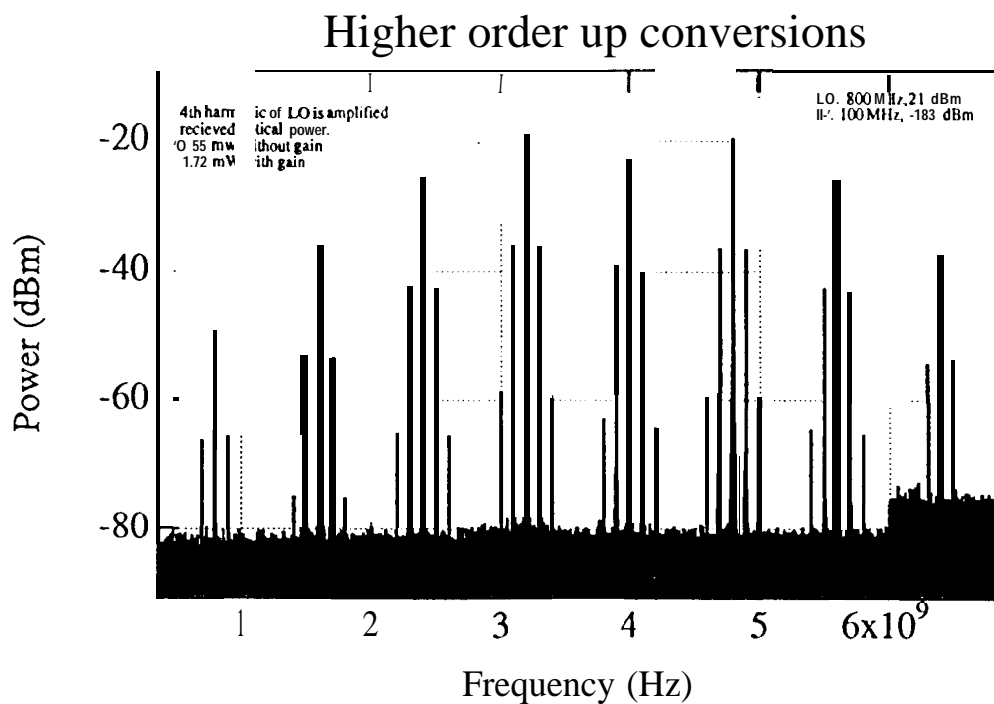
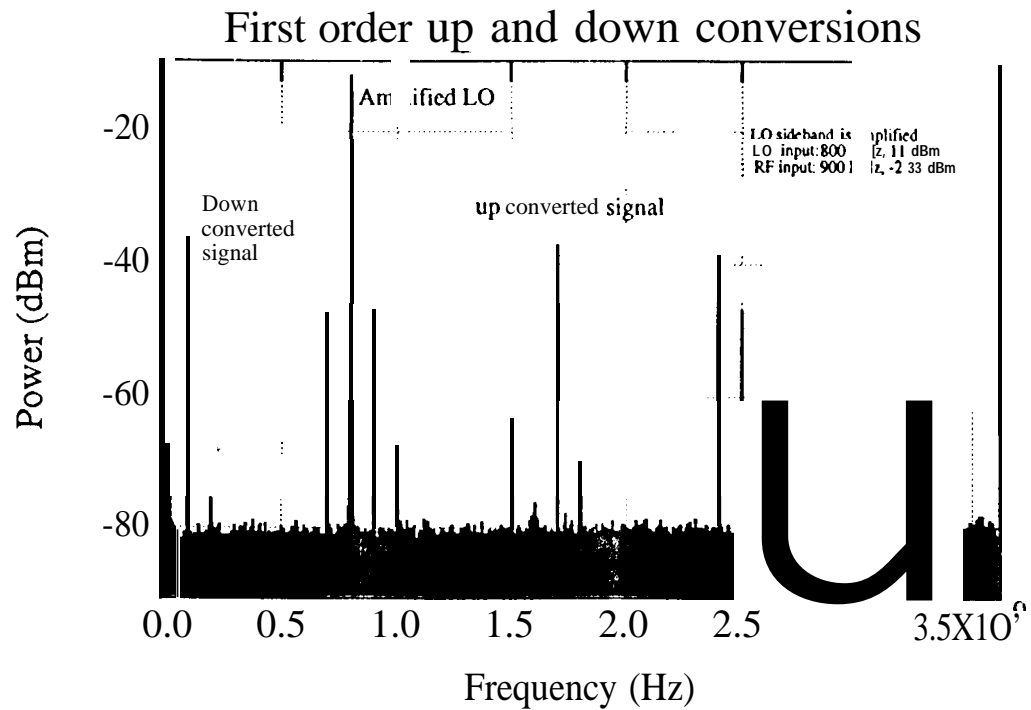


Applications of Brillouin Amplification

5) Signal mixing & multiplication with phase modulators



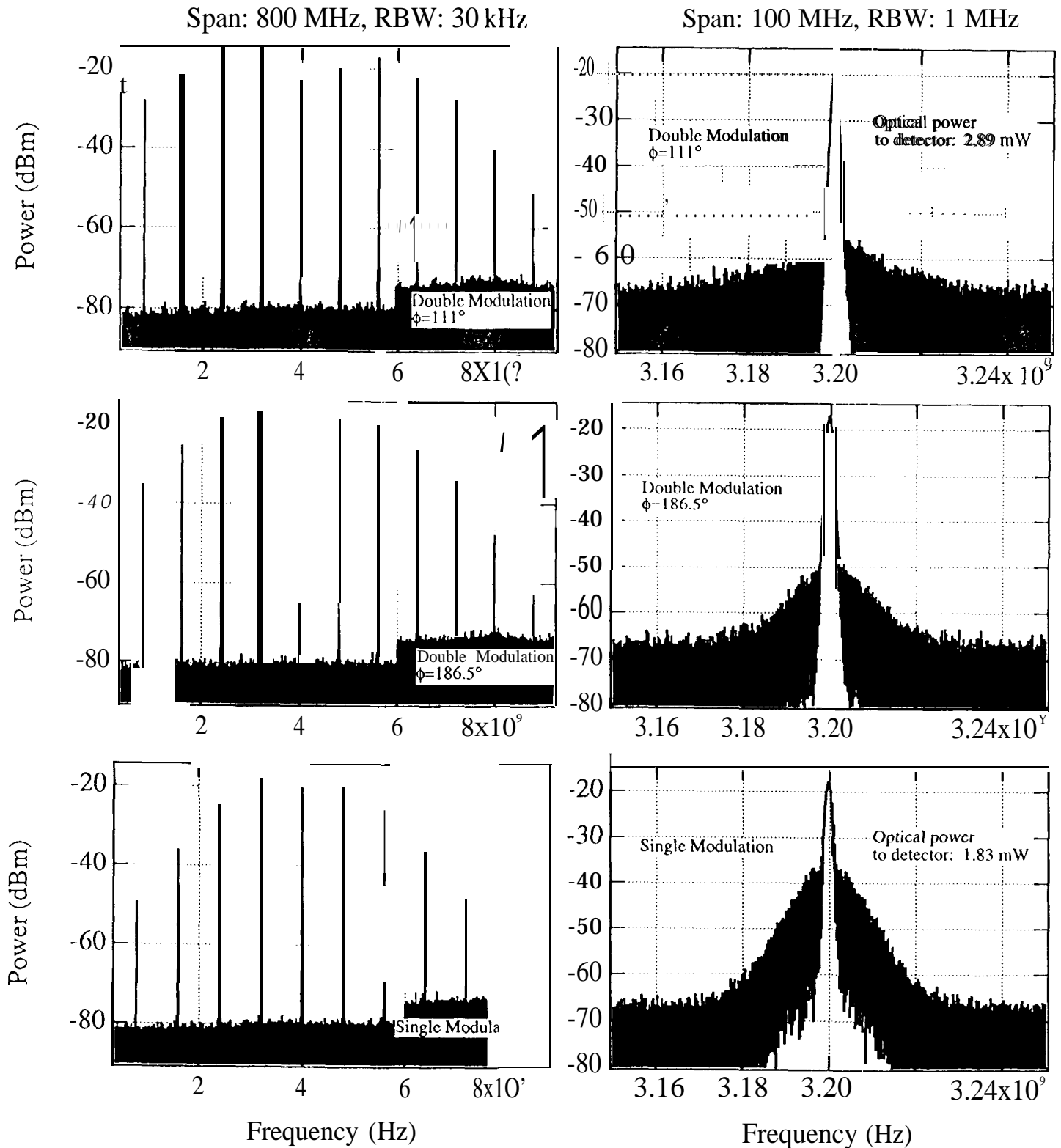
Photonic Mixing with PM & Brillouin Amplification



12/24/96

Comb Frequency Generation with Double Phase Modulators

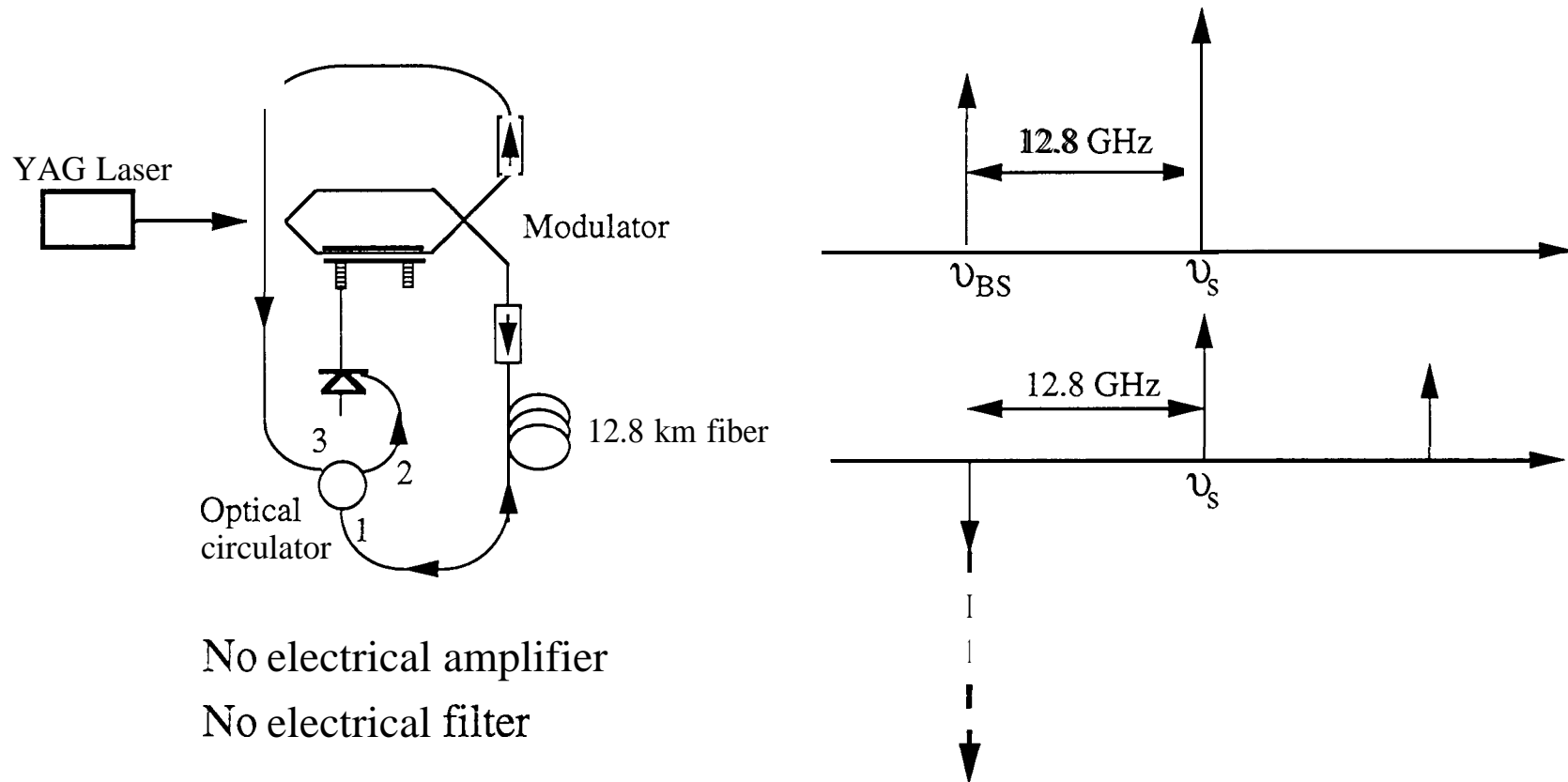
(5th harmonic is amplified with Brillouin Amplification)
Optical power to detector with no amplification: 0.54 mW





Applications of Brillouin Amplification

7) Brillouin Opto-Electronic Oscillator



No electrical amplifier

No electrical filter

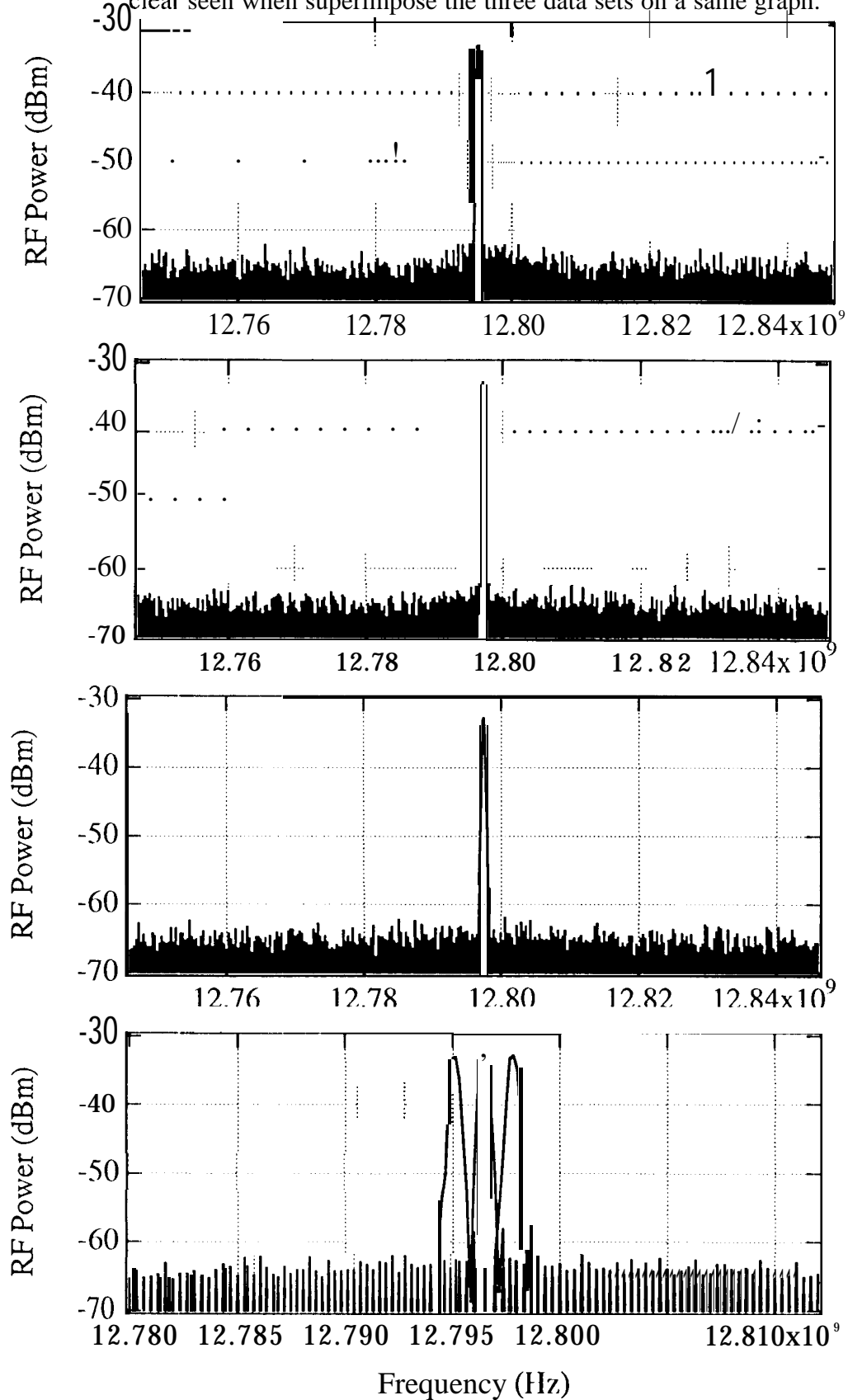
* Using a separate pump laser can make a widely tunable OEO

Brillouin OEO

1/8/96

Span: 100 MHz, RBW: 300 kHz

Three data set are taken at different time. Mode hopping is clear seen when superimpose the three data sets on a same graph.





Summary

- 1) Discussed Brillouin scattering & its properties
- 2) Introduced the powerful selective sideband amplification concept
- 3) Presented Brillouin sideband amplification experimental results
- 4) Discussed Advantages & Limitations
- 5) Presented experimental results of the following applications
 - i) Single tune amplification
 - ii) FM & PM communication with agile tunability.
 - iii) Photonic signal up & down conversion with gain
 - iv) PM to AM conversion
 - v) Simultaneous signal mixing and multiplication with gain
 - vi) Frequency multiplication & frequency comb generation
 - vii) Brillouin Optoelectronic Oscillator